Presence in Virtual Environments:
Visual Factors and Measure Convergence

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Authorization to Submit Dissertation

This dissertation of William Felton, submitted for the degree of Doctor of Philosophy with a Major in Experimental Psychology and titled "Presence in Virtual Environments: Visual Factors and Measure Convergence," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Virtual presence, the subjective sense of reality within a computer-generated environment, is arguably the most important psychological variable in the discussion of virtual environment technology; virtual presence is the defining feature of modern virtual environments, it is the reality of "virtual reality" technology. Despite the importance of this topic, we know little about what factors enhance virtual presence or how to best measure the phenomenon. In this study, I advance our knowledge by investigating two unexplored visual factors of virtual presence: environmental color and lighting quality. Further, I investigate the correlation of two widely used virtual presence measures for the first time: the Slater-Usoh-Steed (SUS) Questionnaire and the Presence Questionaire (PQ v.3). Finally, I introduce a new, and arguably improved, measure of virtual presence, the Felton Presence Questionnaire (FPQ), which I compare to these two existing measures. The results of this study indicate that environmental color significantly affects virtual presence, while lighting quality does not. Additionally, each of the three measures, the SUS, the PQ v.3, and the FPQ, demonstrated high inter-measure correlations, providing evidence that each one is measuring the same underlying construct. Further, the FPQ, which I advance as an improved measure of virtual presence in theory, demonstrates strong reliability compared to the SUS and PQ v.3. These results indicate that efforts to increase virtual presence should focus on environmental color over lighting quality. Further, these results indicate that the SUS, the PQ v.3, and the FPQ are measuring the same underlying construct.

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Dedication

For Cora

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Table 1: Past Definitions of Presence

Author(s)	Conceptualization of Presence
Baumgartner et al (2008, p2)	"presence is defined as an egocentric spatial experience of VEs [VR environments]"
Coelho et al. (2006, p27)	"presence is a psychological state or a subjective perception in which the participant, although working with an instrument, fails to understand the role of technology in his experience"
Draper et al. (1998, p356)	"[presence is] a mental state in which a user feels physically present within the computer-mediated environment"
Draper et al. (1999, p350)	"[presence is] an experience that involves displacement of the user's self-perception into a computer-mediated environment"
Gorini et al. (2011, p99)	"[presence is] a technology-induced illusion of being present in one (simulated) place when one is actually present in another (physical) place"
Herrera et al. (2005); as quoted by Skarbez et al. (2017, p14)	"[presence is] conscious awareness of self, as both agent and experiencer, which characterizes the experiencing self of natural environments"
Ijsselsteijn et al. (2001, p2)	"presence is the experience of projecting one's mind through media to other places, people, and designed environments"
International Society for Presence Research (2000); as quoted by Nowak et al. (2008, p259)	"[presence is] a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of technology in the experience."
Jancke et al. (2009, p52)	"presence is understood to refer to the subjective feeling of being in a virtual environment while being transiently

	unaware of one's real location and surroundings and of the technology that delivers the stream of virtual input to the senses"
Jerome & Jordan (2007, p75)	"presence is thus a psychological phenomenon through which our cognitive processes are oriented toward either the physical environment or a simulated world"
Kuzmicova (2012, p23)	"[presence is] the sense of having physically entered a tangible environment"
Lee (2004, p494)	"presence is broadly defined as 'a psychological state in which the virtuality of experience is unnoticed'"
Lee (2004a, p27)	"[presence is] a psychological state in which virtual objects are experienced as actual objects in either sensory or nonsensory ways"
Lombard & Ditton (1997, p11)	"[presence is] the perceptual illusion of non-mediation"
McCreery et al. (2013, p1635)	"[presence is] the psychological state where virtual experiences feel authentic"
Nichols et al. (1999, p472)	"[presence is] a sense of being there, reflected by engrossment with, and intuitive behaviour in, the VE"
North & North (2018, p79)	"presence is the perception of being physically present in a computer generated or remote environment"
Parola et al. (2016, p1)	"[presence is the] sense of feeling real"
Ratan et al. (2007, p167)	"presence is treated here as the perception (or misperception) that a virtual experience is actually a real experience"
Reiner (2004p 392)	"presence may be considered as a mental state that emerges out of sensory stimulus and bodily interaction with the environment"
Sas & O'Hare (2003, p1)	"presence is a psychological phenomenon, through which one's cognitive processes are oriented toward

	another world, either technologically mediated or imaginary, to such an extent that he or she experiences mentally the state of being (there)"
Schloerb (1995); as quoted by Huang & Alessi (1999a, p2)	"[presence is the] probability that a person perceives that he or she is physically present in the given environment"
Seth et al. (2012); as quoted by Parola et al. (2016; p1)	"[presence is the] subjective veridicality of perceptual processing"
Sheridan (1992a, p120)	"[presence is the] sense of being physically present with visual, auditory or force displays generated by a computer"
Sheridan (1994, p1073)	"[presence occurs] wherein the human participant feels herself to be present at a location which is synthetic, created only by a computer and various visual, auditory or haptic displays"
Skarbez et al. (2017)	"[presence is] the cognitive feeling of being in a place"
Slater (2004a, p2)	"presence is about form, the extent to which the unification of simulated sensory data and perceptual processing produces a coherent 'place' that you are 'in' and in which there may be the potential for you to act"
Slater & Usoh (1993, p221)	"[presence is] the (suspension of dis-) belief that they are in a world other than where their real bodies are located"
Spagnolli et al. (2004, p51)	"definition of presence as distributed on the heterogeneous ensemble of resources that converge on action"
Steuer (1992, p6)	"'presence' refers to the *natural* perception of an environment [emphasis in original]"
Stoffregen et al. (2003, p122)	"[presence is] an illusory (false) perception that the simulator is the simulated"

Waterworth & Waterworth (2003, p3)	"presence is the feeling of being bodily in an externally-existing world"
Wirth et al. (2004, p354)	"[presence is] the subjective experience of being in the mediated environment"
Wirth et al. (2007, p497)	"spatial presence is a binary experience, during which perceived self-location and, in most cases, perceived action possibilities are connected to a mediated spatial environment, and mental capacities are bound by the mediated environment instead of reality"
Witmer & Singer (1998, p225)	"presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another"
Witmer et al. (2005, p298)	"presence is a psychological state of 'being there' mediated by an environment that engages our senses, captures our attention, and fosters our active involvement"
Zahorik & Jenison (1998, p87)	"presence is tantamount to successfully supported action in the environment"

Table 2: Visual Factors on Virtual Presence (Inferential Statistics)

	Color (main effect)	**Shadow (main effect)**	**Color x Shadow (interaction)**
SUS	$F(1, 54) = 13.24$, $p < .01$, $\eta_p^2 = .20$	$F(1, 54) = 1.53$, $p = .22$, $\eta_p^2 = .03$	$F(1, 54) = .03$, $p = .86$, $\eta_p^2 = .00$
PQ	$F(1, 54) = 28.15$, $p < .01$, $\eta_p^2 = .34$	$F(1, 54) = 2.83$, $p = .10$, $\eta_p^2 = .05$	$F(1, 54) = 1.27$, $p = .27$, $\eta_p^2 = .02$
FPQ	$F(1, 54) = 27.02$, $p < .01$, $\eta_p^2 = .33$	$F(1, 54) = 2.02$, $p = .16$, $\eta_p^2 = .04$	$F(1, 54) = .00$, $p = .98$, $\eta_p^2 = .00$

Table 3: Visual Factors on Virtual Presence (Descriptive Statistics)

	Color-Shadow	Color-No Shadow	Gray-Shadow	Gray - No Shadow
SUS	*M* = 4.34 *SD* = 1.27	*M* = 4.32 *SD* = 1.13	*M* = 4.00 *SD* = 1.27	*M* = 3.98 *SD* = 1.30
PQ	*M* = 4.51 *SD* = .70	*M* = 4.51 *SD* = .68	*M* = 4.34 *SD* = .69	*M* = 4.28 *SD* = .69
FPQ	*M* = 4.49 *SD* = 1.33	*M* = 4.44 *SD* = 1.33	*M* = 4.01 *SD* = 1.22	*M* = 4.00 *SD* = 1.25

	Color	Gray	Shadow	No Shadow
SUS	*M* = 4.33 *SD* = 1.20	*M* = 3.99 *SD* = 1.28	*M* = 4.18 *SD* = 1.28	*M* = 4.15 *SD* = 1.22
PQ	*M* = 4.51 *SD* = .70	*M* = 4.31 *SD* = .69	*M* = 4.43 *SD* = .70	*M* = 4.39 *SD* = .69
FPQ	*M* = 4.46 *SD* = 1.33	*M* = 4.00 *SD* = 1.23	*M* = 4.25 *SD* = 1.30	*M* = 4.42 *SD* = 1.30

Table 4: Virtual Presence Inter-Measure Correlations

Measure	M	SD	1	2	3
1. SUS	4.24	1.34	1.0		
2. PQ	4.41	.66	.59	1.0	
3. FPQ	4.22	1.19	.79	.72	1.0

Table 5: Virtual Presence Measures – Item Reliability Across Trials

SUS (one factor)

Factor (items)	Trial 1	Trial 2	Trial 3	Trial 4
Spatial Presence (6)	Cronbach's α = .71	Cronbach's α = .81	Cronbach's α = .88	Cronbach's α = .91

PQ (four factors)

Factor (items)	Trial 1	Trial 2	Trial 3	Trial 4
Involvement (12)	Cronbach's α = .81	Cronbach's α = .88	Cronbach's α = .89	Cronbach's α = .90
Sensory Fidelity (6)	Cronbach's α = .63	Cronbach's α = .62	Cronbach's α = .66	Cronbach's α = .66
Adaptation / Immersion (8)	Cronbach's α = .81	Cronbach's α = .80	Cronbach's α = .86	Cronbach's α = .86
Interface Quality (3)	Cronbach's α = .55	Cronbach's α = .47	Cronbach's α = .65	Cronbach's α = .51

FPQ (one factor)

Factor (items)	Trial 1	Trial 2	Trial 3	Trial 4
Spatial Presence (5)	Cronbach's α = .78	Cronbach's α = .82	Cronbach's α = .86	Cronbach's α = .89

Table 6: Virtual Presence Measure Inter-Trial Reliability (Test-Retest Reliability)

SUS

Trial	M	SD	1	2	3	4
1. Trial 1	4.29	1.04	1.0			
2. Trial 2	4.25	1.08	.66	1.0		
3. Trial 3	4.17	1.34	.60	.83	1.0	
4. Trial 4	4.03	1.49	.63	.85	.88	1.0

PQ

Trial	M	SD	1	2	3	4
1. Trial 1	4.36	.61	1.0			
2. Trial 2	4.47	.66	.86	1.0		
3. Trial 3	4.42	.71	.74	.88	1.0	
4. Trial 4	4.44	.79	.73	.88	.915	1.0

FPQ

Trial	M	SD	1	2	3	4
1. Trial 1	4.24	1.10	1.0			
2. Trial 2	4.28	1.24	.84	1.0		
3. Trial 3	4.23	1.34	.64	.76	1.0	
4. Trial 4	4.19	1.45	.66	.82	.84	1.0

Table 7: Covariates of Virtual Presence

	SUS	PQ	FPQ
Participant Age	$r(58) = -.20$, $p = .12$	$r(58) = -.25$, $p = .06$	$r(58) = -.22$, $p = .10$
Participant Sex	$t(57) = -.61$, $p = .55$, $d = .16$	$t(57) = .17$, $p = .87$, $d = .04$	$t(57) = .61$, $p =.55$, $d = .16$
Videogame Playing	$r(58) = .17$, $p = .19$	$r(58) = .23$, $p = .09$	$r(58) = .10$, $p = .46$
Trial Number	$F(3, 162) = 1.73$, $p = .16$, $\eta_p^2 = .03$	$F(3, 162) = 1.45$, $p = .23$, $\eta_p^2 = .03$	$F(3, 162) = .20$, $p = .90$, $\eta_p^2 = .00$
VE Starting Location	$F(3, 162) = 1.93$, $p = .13$, $\eta_p^2 = .04$	$F(3, 162) = 1.95$, $p = .12$, $\eta_p^2 = .04$	$F(3, 162) = 1.50$, $p = .22$, $\eta_p^2 = .027$
Recruitment Method	$t(57) = .76$, $p = .45$, $d = .20$	$t(57) = .26$, $p = .81$, $d = .06$	$t(57) = .11$, $p = .91$, $d = .03$
Questionnaire Order	$t(57) = -1.95$, $p = .06$, $d = .51$	$t(57) = -1.50$, $p = .14$, $d = .39$	$t(57) = -2.25$, $p = .03$, $d = .59$
Research Assistant	$F(3, 54) = .18$, $p = .91$, $\eta_p^2 = .01$	$F(3, 54) = .70$, $p = .56$, $\eta_p^2 = .04$	$F(3, 54) = 2.84$, $p = .05$, $\eta_p^2 = .13$
Inferred Purpose	$t(56) = -.75$, $p = .46$, $d = .22$	$t(56) = -.48$, $p = .63$, $d = .14$	$t(56) = -.12$, $p = .91$, $d = .03$

Table 8: Targets Found – Visual Factors (Descriptive Statistics)

	Color-Shadow	**Color-No Shadow**	**Gray-Shadow**	**Gray - No Shadow**
Targets Found	*M* = 8.24 *SD* = 2.52	*M* = 8.0 *SD* = 2.43	*M* = 7.87 *SD* = 2.27	*M* = 7.78 *SD* = 2.52

	Color	**Gray**	**Shadow**	**No Shadow**
Targets Found	*M* = 8.12 *SD* = 2.46	*M* = 7.82 *SD* = 2.39	*M* = 7.94 *SD* = 2.34	*M* = 7.89 *SD* = 2.47

Table 9: Targets Found – Visual Factors and Additional Covariates

	Targets Found
Color (Main Effect)	$F(1,53) = 2.05$, $p = .16$, $\eta_p^2 = .04$
Shadow (Main Effect)	$F(1,53) = .71$, $p = .40$, $\eta_p^2 = .01$
Color x Shadow (Interaction)	$F(1,53) = .02$, $p = .88$, $\eta_p^2 = .00$
Participant Age	$r(58) = -.03$, $p = .80$
Participant Sex	$t(57) = -3.81$, $p <.01$, $d = .99$
Videogame Playing	$r(58) = .21$, $p = .12$
Trial Number	$F(3, 159) = 12.32$, $p < .01$, $\eta_p^2 = .19$
VE Starting Location	$F(3, 159) = 5.03$, $p < .01$, $\eta_p^2 = .09$
Recruitment Method	$t(57) = -.022$, $p = .98$, $d = .01$
Research Assistant	$F(3, 55) = .23$, $p = .87$, $\eta_p^2 = .01$
Inferred Purpose	$t(56) = -.91$, $p = .37$, $d = .21$

Table 10: Targets Found and Virtual Presence Measure Correlations.

	SUS	**PQ**	**FPQ**
Targets Found	$r(58) = .12, p = .39$	$r(58) = .08, p = .57$	$r(58) = -.10, p = .47$

Chapter 1: Introduction

1. Study Purpose

In this dissertation, I describe a study which I conducted to investigate the psychological construct of presence. I define presence here as *the extent to which something (environment, person, object, or any other stimulus) appears to exist in the same physical world as the observer.* More generally, the construct of presence can be understood as one's perception of reality; it is the experience that something (some place, person, object, or other stimulus) is real. Of particular interest in this work is presence as it occurs in a virtual environment (VE), in which the user experiences a compelling sense of reality in a computer-generated virtual world. I refer to this phenomenon as *virtual presence,* as do others in the field (e.g., Sheridan, 1994). Specifically, I conducted a study which investigated the effect of two visual factors, environmental color (the depiction or absence of color in the VE) and lighting quality (the depiction or absence of shadows in the VE), on virtual presence; in this same study, I measured participant virtual presence with two established measures (the SUS and PQ v.3) and a third measure which I developed (the FPQ) in order to determine if these three measures are measuring the same construct.

The investigation of these two visual factors is important for several reasons. First, there is limited prior research on these factors. Following an extensive review of the literature, I am aware of only one study which investigates lighting quality as a factor of virtual presence (see Slater et al., 1995), but this prior work has major methodological flaws. Slater et al. conclude that higher lighting quality (the addition of object shadows) increases virtual presence, but they test a small sample size (eight total) of workplace colleagues with an extremely low quality display (340 x 240 pixels, 75˚ field-of-view, eight frames-per-second). I know of no prior research which manipulates environmental color as a factor of virtual presence. As such, this study investigates a wholly unexplored factor of virtual presence (environmental color), as well as an effectively unexplored factor (lighting quality).

Second, the factors that I have chosen are manipulable by VE content-creators. As I discuss at length later, applied VEs are used across domains (e.g., in entertainment, in research, in training, in therapy, etc.) and maintaining virtual presence is a core requirement in these applications (Chapter 1: Section 2; Appendix C). Research on manipulable factors, such as environmental color and lighting quality, is useful to both an academic and applied audience; research on non-manipulable factors (e.g., user personality or display hardware) still informs our knowledge, though its applied importance is comparatively limited.

Third, past researchers have rarely employed factorial designs in the study of virtual presence factors, which I do in this study to explore the potential of both main effects and interaction effects.

Finally, prior research on virtual presence, given the rapid advancement of VE technology, is becoming quickly outdated. For example, in a relatively recent study, Nystad and Sebok (2004) conducted a study on virtual presence using a monoscopic head-mounted display (i.e., headset) with a 55˚ field-of-view and an 800 x 600 pixel display. Nystad and Sebok's results, and the results of numerous past studies which date to the 1990s or earlier, are unlikely to generalize to modern display systems. In my study, I used the HTC Vive Pro (a stereoscopic display, with a 110˚ field-of-view, and a 1440 x 1600 pixel resolution per eye). Given that virtual presence is inherently enmeshed with technology, it is critical that we update past results with modern technologies.

The comparison of virtual presence measures in this study is likewise important for this field. To date, virtual presence researchers have employed a broad range of measures (Chapter 2: Section 7). Unfortunately, many of these measures, including extremely common measures, are thought to have questionable validity. For example, two popular measures of virtual presence, the Slater-Usoh-Steed (SUS; Usoh et al., 2000) and the Presence Questionnaire (PQ v.3; Witmer et al., 2005), are thought to be measuring different constructs. The respective authors themselves have argued that their measures are divergent: Witmer et al. (2005), the authors of the PQ v.3, argue that the SUS consists of "only a small number of relatively homogenous, face-valid items" (p300) while Slater (1999), an author of the SUS, wrote a paper specifically to address why he "would never use the W&S questionnaire [the Witmer and Singer PQ] for studying presence" (p561). In order to test this perceived difference among the measures, I employ both the SUS and the PQ v.3 in this study to gauge whether their scores correlate within the same individuals. While previous authors have compared the SUS and earlier versions of the PQ (v.1 and v.2), indicating both a significant correlation (Kober & Neuper, 2012) and a significant difference (Nystad & Sebok, 2004), no researcher has compared the SUS to the latest version of the PQ (v.3).

There is reason to believe that the PQ v.3 and the SUS may no longer diverge, given that the PQ v.3 uses different items, fewer items, updated item wording, and consists of fewer sub-factors, than the original questionnaire (Witmer & Singer, 1994; Witmer et al., 2005).

Further, much of the past research which compares the SUS and the PQ is questionable given the inconsistency in how these same measures have been used in prior studies. For example, past research using the "SUS" includes at least: a three-item version (Slater, et al., 1994), a five-item version (Van Baren & Ijsselsteijn, 2004), a six-item version (Ausburn et al., 2019), and a seven-item version (Usoh et al., 2000); beyond the difference in the number of items, these versions also use different item wording, different response scale formatting, and different scoring procedures. The research using the PQ has likewise been inconsistent. Witmer and Singer (1998) introduce both their 32-item PQ (v.1) and their revised 19-item PQ (v.2) in the same paper, noting that the latter (following a reliability analysis) is more reliable than the original. Researchers have since used the "PQ" in various ways, including at least: 18-items (Nystad & Sebok, 2004), 19-items (Kober & Neuper, 2013), 20-items (Vora et al., 2002), and 32-items (Kober & Neuper, 2012). Further, though the PQ uses semantic differential scales (with adjective anchors for each question), the authors only provide a single item's response scale; it is evident, especially considering that researchers use the PQ with Likert scales (e.g., Nystad & Sebok, 2004), which necessitates a change of the PQ's original item wording, that we are using various versions of the "PQ" across studies.

In this study, I used the six-item SUS: it is the most robust quantitative SUS available, it is advanced by the original authors of the measure, and it has its full items available for consistent replication (Usoh et al., 2000). I used the 29-item PQ v.3 in this study, with slight modifications to item wording to use Likert scales, given that the authors of the PQ argue that it is the most reliable and valid of the three existing versions (Witmer et al., 2005). Further, as I note above, no prior research has compared the PQ v.3 to the full six-item SUS to gauge their degree of convergence.

In addition to using the SUS and PQ v.3, in this study I included an original five-item Felton Presence Questionnaire (FPQ). I compared the FPQ to the SUS and the PQ v.3 in order to compare its results to these commonly used and popular measures. The FPQ, if researchers fully validate the measure, would advance our measurement of virtual presence in important ways. First, the FPQ conceptualizes the experience of virtual presence in a novel way, as both as "being in" a VE which feels real (Appendix I: Items F.1-F.2) and as "being out" of the physical environment (Appendix I: Items F.3-F.5). Second, the FPQ is substantially shorter than many existing presence measures: it is roughly one-sixth the length of the PQ v.3 (29 items) and one-fifteenth the length of the Reality Judgment and Presence Questionnaire (77 items; see Van Baren & Ijsselsteijn, 2004). Third, the FPQ uses Likert scoring, so the data allows for more robust analyses than certain existing measures; for example, the standard scoring of the SUS suggests a dichotomous count of "low" and "high" scoring items (e.g., see Slater, Usoh, et al., 1994), however, this scoring procedure for standard Likert data is less robust and the definition of "high" scoring items (for responses of six or seven) is arbitrary. Fourth, the FPQ items are more concise, and arguably, more understandable than certain existing measure items (e.g., compared to the SUS Item 5; Appendix I: Item S.5). Finally, the FPQ does not ask participants about their sense of "presence" directly, which, despite being a known issue in the field (e.g., see Sandowski & Stanney, 2002; Slater, 2004), remains a strikingly common feature in current measures. Van Baren and Ijsselsteijn's virtual presence measure compendium highlights the prevalence of this issue, given that half of the questionnaires in their appendix (ten out of 20 total measures) include items which explicitly ask about "presence." Following my review of the literature, and a review of Van Baren and Ijsselsteijn's compendium, I am not aware of any other existing measure which combines these five advantages.

This study, therefore, has two primary goals: 1) to investigate the effect of environmental color and lighting quality on virtual presence, and 2) to determine if three measures of virtual presence correlate, as would be expected if they are each measuring the same construct.

2. Problem Significance: Why Research Virtual Presence

Virtual presence is the most important psychological phenomenon in the discussion of VEs; it is the reason that the virtual world feels viscerally real to the user. When we discuss the user's experience of "virtual *reality*" (VR) we are discussing virtual presence. Researchers consistently reaffirm the significance of virtual presence and repeatedly acknowledge that it is the defining feature of modern VE technology (Bergstrom et al., 2017; Biocca, 1997; Hodges et al., 1994; Hvass et al., 2017; Mazuryk & Gervautz, 1996;

Slater, Usoh, & Chrysanthou, 1995; Steuer, 1992; Waterworth & Waterworth, 2001; Zeltzer, 1992; etc.). Unfortunately, we do not know which VE factors most influence the user's experience of virtual presence (Ellis, 1996; Freeman et al., 2000; Held & Durlach, 1991; Hodges et al., 1994; Ijsselsteijn, 2002; Jelfs & Whitelock, 2000; Lombard & Ditton, 1997; Slater, Usoh & Steed, 1995; etc.). We likewise do not know how to best measure virtual presence (Schuemie et al., 2001; Ijsselsteijn et al., 2001; Van Baren & Ijsselsteijn, 2004, etc.). As such, determining which factors most affect virtual presence and identifying the most appropriate measures of the phenomenon are fundamental goals in the field.

Understanding virtual presence is also significant given the increasing applied uses for VE technology, which I overview briefly below (Chapter 1: Sections 2.1-2.9), as a supplement, I provide an extended review of these topics as appendixes (Appendixes C-E).

2.1 Educational Significance

Educators are expanding their use of VEs in the classroom, a practice observable from grade school education (Bayon et al., 2003) through medical school residencies (Seymour et al., 2002). For example, in early education research, VEs aid students in learning teamwork (Roussos et al., 1997), reading (Bayon et al., 2003), and zoology (Allison et al., 1997). Among high school and university students, Brelsford (1993) demonstrated that a physics lecture given with a VE learning aid resulted in significantly higher learning and retention, compared to a standard lecture. These findings are generalizable to the highest levels of education. Seymour et al., in a randomized double-blind study investigating the effect of a VE teaching aid for surgical resident training, found that those in the VE learning group completed their surgical exam 29% faster and with 16% as many errors as those in the traditional learning group.

Though several factors may contribute to the above effects, education researchers repeatedly note that, when using a VE teaching aid, the learner's experience of virtual presence is critical to their learning outcome. As Winn (1993) states, when students experience virtual presence their learning is of "the same quality as our experiences in the real-world" (p3), which enhances their learning compared to other techniques (e.g., reading a textbook). Mikropoulous and Strouboulis (2004) reiterate the importance of virtual presence on VE learning aids, as they emphasize that student virtual presence correlates with enhanced cognitive performance and emotional development. Similarly, Whitelock et al.

(2000) and Chang (2009) each note that virtual presence tends to increase students learning motivation and interest in the course material.

Given these benefits, education researchers are actively seeking which factors most increase virtual presence (e.g., Jelfs & Whitelock, 2000). However, as Jelfs and Whitelock note, we still do not know which factors most increase virtual presence, nor do we know how to accurately measure virtual presence. My study, which investigates two visual factors across three measures of virtual presence, advances our knowledge in both of these domains.

2.2 Training Significance

VEs are a unique training tool compared to traditional training methods, in that VE based training is often safer, less expensive, and more readily customizable than in-person training (Anderson et al., 1997; Loren, 2012; U.S. Congress, 1994). There are ample examples of VE-based training in the literature including laparoscopic surgery training (Seymour et al., 2002), military personnel training (U.S. Congress, 1994), aircraft fault inspection training (Vora et al., 2002), industrial mining training (Tichon & Burgess-Limerick, 2011), workplace safety training (Sacks et al., 2013) and neurosurgery training (Alaraj et al., 2011).

Of the many examples, the training conducted by the U.S. Department of Defense (DoD) most exemplifies the unique advantages of using a VE to more efficiently train complex and dangerous skillsets. The DoD has used VEs to train aviation (U.S. Congress, 1994), vehicle rollover procedures (Wells, 2010), distance estimation to enemy combatants (Lampton et al., 1995), small unit decision making (Hill et al., 2003), wayfinding (Darken et al., 1997), combat communication (Loren, 2012), firearms training (U.S. Army, 2019) and close quarter combat with vehicle support (U.S. Army, 2010). The DoD acknowledges the importance of virtual presence, and many training officers specifically stress the value of trainee virtual presence on their performance outcomes (e.g., Chang, 2009; U.S. Army, 2010; Wells, 2010). Additionally, academic researchers argue that virtual presence is foundational for training outcomes, in that the strength of one's virtual presence should reflect their real-world behavior (see Calvert & Tan, 1994; Nowak et al., 2008; Rosenberg et al., 2013). Bystrom et al. (1999) state the importance of virtual presence on performance in stronger terms, arguing that the "sense of presence in an environment is a necessary condition for performance to occur" (p242).

Through an understanding of virtual presence factors, the DoD, and other organizational trainers, can maximize their VE training efficacy and derive the most value from their training procedures.

2.3 Medical Significance

Clinicians increasingly use VEs as a medical aid, a notable example being as a treatment for patient pain management. To date, clinicians have used VEs to treat patient burn pain, cancer pain, and pain from chronic conditions (Li et al., 2011). As Hoffman et al. (2000) acknowledge, VE pain management is especially useful as an alternative to pharmacological (often opiate-based) pain treatments, which are difficult to administer and ineffective for certain patient conditions (Perry et al., 1981). Opiate-based treatments are also particularly addictive and dangerous (Centers for Disease Control, 2019), a fact which is especially salient today given the sharp rise in opiate abuse and the five-fold increase in fatal overdoses since 1999 (Centers for Disease Control, 2019). The societal impact of VE-based pain management is especially hopeful given this context, and researchers (e.g., Das, 2018) suggest that VE-based pain treatments could soon become a viable alternative to opiate-based pain management.

The efficacy of VE-based pain management has support in the empirical research. For example, Hoffman et al. (2000) conclude their study by stating that VEs can “serve as a powerful adjunctive, nonpharmacological analgesic” (p305). Hoffman et al., though their sample size was small, state that patients self-reported roughly half of the pain level while using an immersive head-mounted display (HMD) than while using a non-immersive (monitor-based) display, a finding which Gershon et al. (2004) corroborate in their own study.

Interestingly, while the causal mechanism for VE-based pain reduction remains unclear, a common assumption is that the VE acts as a powerful distraction from the pain source. Gershon et al. theorize that VE pain management is successful because the VE draws limited attentional resources into the virtual world, or virtual task, and away from the source of one’s real-world pain. Hoffman et al. agree with this notion of attentional diversion, adding that the degree of attentional diversion depends on the patient’s degree of virtual presence. Likewise, Li et al. (2011) conclude in their review of VEs for medical applications that the “ability to instantly transport the patient into a virtual world... makes

VR [virtual reality] a tremendously powerful tool" in medicine (p10). As each of these authors highlight, inducing virtual presence is a key factor for this application, this would be especially true if we confirm that the efficacy of VE-based pain management is due to its ability to divert patient attention.

2.4 Clinical Psychological Significance

Academic researchers and clinical psychologists use VEs to research and treat an array of psychological disorders and associated symptomology, including persecutory ideation (Valmaggia et al., 2007), eating disorders (Gutierrez-Maldonado et al., 2006), post-traumatic stress disorder (Goncalves et al., 2012), schizophrenia (Ku et al., 2003), dementia (Flynn et al., 2003), and traumatic brain injury (Lee et al., 2003).

Though clinical psychologists use VEs in a wide range of applications, one of the most common is phobia treatment through virtual reality exposure therapy (VRET) (Gregg & Tarrier, 2007). To date, clinicians have used VRET to treat numerous patient phobias: aerophobia (Rothbaum et al., 2002), arachnophobia (Carlin et al., 1997), acrophobia (Emmelkamp et al., 2002), agoraphobia (Viaud-Delmon et al., 2006), cynophobia (Taffou et al., 2012), anorexia nervosa (Gutierrez-Maldonado et al., 2006), driving phobia (Walshe et al., 2003), and others (Gregg & Tarrier, 2007).

VRET has significant advantages over the two main treatment alternatives: imaginal exposure and in-vivo exposure (Alsina-Jurnet et al., 2007). VRET is more effective than imaginal exposure and more practical than in-vivo exposure (Alsina-Jurnet et al., 2007), and further, there is evidence that VRET is as effective as in-vivo exposure, the current gold standard in phobia treatment (Alsina-Jurnet et al., 2011; Emmelkamp et al., 2002). Perhaps unsurprisingly, researchers have demonstrated that virtual presence is essential in phobia treatment outcome (Alsina-Jurnet et al., 2011; Ling et al., 2014).

2.5 Research Significance

In academia, researchers use VE technology to study a variety of phenomena. This practice is prevalent in psychology research, where researchers have used VEs to investigate psychological disorders (Gregg & Tarrier, 2007), psychomotor action (Mason et al., 2001), distance perception (Kline & Witmer, 1996; Jackson et al., 2013), interpersonal social dynamics (Bailenson & Yee, 2008), and reality judgment (Usoh et al., 2000).

VE technology offers two major advantages as a research tool. First, VEs afford the researcher a high degree of experimental control. For example, the researcher can program the VE to control for extraneous environmental variables, which helps to ensure that experimental conditions are consistent across participants. Second, VE technology, given that it often induces virtual presence, increases the ecological validity of the study. Virtual presence indicates that one's virtual behavior reflects their real-world behavior (Fox, Bailenson, et al., 2009), so by measuring the participants' virtual presence, one can infer the generalizability of laboratory findings to real-world human behavior. Given these attributes, the experimenter gains both high internal validity and a means to infer ecological validity.

This said, academic researchers face two challenges while using VEs in research. First, as I note above, we do not know which factors most enhance virtual presence in a participant (to enhance ecological validity). Second, we do not know if virtual presence measures are truly measuring the construct (to accurately infer ecological validity). The results of my study, in which I compared two common measures of virtual presence and a newly developed measure, provides empirical evidence to address these issues.

2.6 Legal Significance

An understanding of virtual presence is essential to the emerging legal issues concerning modern VEs. Modern multiplayer VEs allow large numbers of users the ability to interact in real time, and as an unfortunate result, user misconduct and legal recourse is becoming increasingly common. A particularly complex issue is VE "street crime," in which a user (through their virtual avatar) harasses, assaults, threatens, stalks, or otherwise attempts to harm another user (Lemley & Volokh, 2018). VE users perceive virtual street crime as more harmful when they experience virtual presence, and researchers have demonstrated that virtual presence heightens the perception that a virtual danger is viscerally harmful (Slater, Usoh & Steed, 1994; Slater, Usoh & Steed, 1995; Zimmons & Panter, 2003). The issue of virtual presence increasing the perception of a VE danger is especially troubling when considering children in VEs, given the evidence that children cannot inhibit the experience of virtual presence as can adults (Baumgartner et al., 2008; Liao et al., 2019).

The issue of VE law, and the impact of virtual presence on legal decisions, is not rhetorical debate. Legal scholars note that cases of VE street crime are appearing in real-world courts, including cases of "virtual rape," "virtual murder," user harassment, user cyber stalking, and the intent to cause real-world harm (Lastowka & Hunter, 2004; Lemley & Volokh, 2018). Given that jurists acknowledge that virtual presence is a factor in the issue of virtual street crimes (e.g., Lemley & Volokh, 2018), our understanding of virtual presence, including its factors and measurement, is increasingly important.

2.7 Ethical Significance

Researchers commonly voice ethical concerns about VE technology, and particularly common are concerns about violent content (and violent behavioral transfer), user escapism, user addiction, and the impact of presence-inducing technology on mental health (Huang & Alessi, 1999; Ichimura et al., 2001; Marshall, 2016; Sheridan, 1993; Whitby, 1993). Though scholars have identified similar ethical concerns with past medias, such as with literature (Boyer, 1963) and with film (Rosenbloom, 2004), Whitbeck (1993) notes that VEs are inherently different, in that the VE user experiences an enhanced sense of reality (i.e., virtual presence) and a sense of causal agency over their actions. According to Whitbeck this combination of enhanced presence and user causal agency, where the user is an active participant in a compelling realistic scene, warrants additional scrutiny of appropriate content. Other researchers reiterate similar points, arguing that the ability of modern VEs to induce a strong sense of virtual presence in itself justifies careful ethical considerations (Beardon, 1992; Marshall, 2016; Nowak et al., 2008; Sheridan, 1993; etc.). As Beardon argues regarding VEs, “the responsibilities of the author of that reality are no less than the person who administers a consciousness controlling drug, and the ethical principles which that person works under should be no less severe” (p27).

By understanding which factors most enhance, or most diminish, virtual presence, VE content creators can induce an optimal level of user virtual presence to mitigate the ethical issues accompanying modern VEs. For example, VE content creators, especially if the content is violent, may choose (or be required) to lower the anticipated level of user virtual presence. An understanding of which factors most increase or decrease virtual presence, and how to reliably measure the experience, would be criticial to this goal.

2.8 Theoretical Significance

Psychologists from the founding of psychological science (e.g., James, 1890) through the present day (e.g., Lauria, 1997) have indicated that understanding our experience of reality (i.e., presence) is a core psychological pursuit. The importance that psychologists place on presence is observable in the earliest of psychological texts, such as William James' (1890) *The Principles of Psychology*, in which James devotes a chapter to the experience of reality. Biocca (1997) dates the study of presence further into our history, suggesting that understanding our perception of reality is an ancient human desire; this view has some credence, considering the early philosophical writings on the nature of reality judgment (e.g., Plato, c.375 B.C.).

The mystery surrounding our experience of reality is brought to the forefront with modern, and increasingly advanced, VE technology. As Biocca (1997) notes, the advent of the modern VE "and the strong sense of being there [virtual presence] that it generates is often accompanied by questions about the stability of our perception of the physical world... if the senses can be so easily fooled, then how can we trust the day-to-day experience of physical reality?" (p15). Loomis (1992) articulates similar questions, suggesting that VEs "can be so compelling as to force a user to question the assumption that the physical and perceptual worlds are one and the same" (p113). The experience of virtual presence can challenge our understanding of physical reality, but inversely, the experience of virtual presence allows researchers, for the first time, to empirically investigate the factors that determine our perception of reality. The strength of virtual presence depends on a number of technological and individual factors, and through an investigation of these factors, we can ultimately enhance our understanding of physical reality perception.

Chapter 2: Literature Review

1. Scope of Review

In the following review of the literature, I provide a condensed survey of the topics which are most relevant to this study. I discuss VE technology with a focus on how VEs are used in psychological research and I discuss virtual presence with an emphasis on the known factors of virtual presence and its measurement. I provide an extended literature review of these topics, and other auxiliary topics, at the end of this paper (Appendixes A-H).

Following this focused literature review, I detail the study method (Chapter 3), study results (Chapter 4), and study conclusions (Chapter 5).

2. Virtual Environment (VE) Criteria

As I define it here, a VE meets two criteria: 1) it is computer-generated with a visual display medium and 2) it affords user action within the computer-generated environment. An immersive VE has two additional criteria: 3) the visual display medium limits user visual perception to the computer-generated environment and 4) the visual display medium uses a head-tracking system which updates the visual scene to corresponding head movement. I base these additional criteria for an immersive VE on those of earlier researchers (Bowman et al., 2001).

3. Head-Mounted Displays (HMDs) in Research

Among VE display types, HMDs are increasingly popular with consumer audiences (Marshall, 2016; Rogers, 2019) and they are increasingly used by researchers (e.g., Fox, Arena, et al., 2009). Among the latter, researchers commonly use HMDs in their experimental procedures, including in the study of persecutory ideation (Valmaggia et al., 2007), distance perception (Kline & Witmer, 1996), anxiety disorders (Alcaniz et al., 2003), and transfer of training (Vora et al., 2002). HMDs provide the researcher with several advantages. First, HMDs fully immerse user vision and occlude the physical world, which limits real-world sensory distraction and limits the influence of extraneous variables. Second, consumer HMDs have practical benefits, including their cost effectiveness, ease of assembly, durable design, and usability in small physical lab spaces. Third, HMDs often use both a binocular display and a head-tracking system, which provides the participant with more natural visual depth cues and realistic kinesthetic cues during the study (Sutherland, 1968). Fourth, HMDs tend to induce a compelling experience of virtual presence compared to other VE displays (Bown et al., 2017; Zanbaka et al., 2004). The participant's enhanced sense of virtual presence while using the HMD is a critical advantage, as it implies that their behavior in the VE will generalize to their real world behavior (Fox, Arena, et al., 2009).

Acknowledging the above advantages, I used a HMD in my own study method.

4. Simulator Sickness

Simulator sickness remains one of the largest challenges to the acceptance of VE technology. Despite their many advantages in research and growing consumer popularity, HMDs have a history of inducing user discomfort, feelings of sickness, physiological changes, and cognitive aftereffects (Nichols et al., 1997; Wilson, 1996). I review simulator sickness extensively elsewhere (Appendix F), and so here, I focus on the effect of simulator sickness on participant drop-out, which is a known impediment to using HMDs in psychological research (e.g., Balk et al., 2013).

Simulator sickness symptoms, including nausea and eye strain, can induce discomfort and contribute to participant drop-out during a study session. For example, Balk et al. (2013) report that, across nine studies, 14% of participants had to drop-out prior to study completion (primarily due to nausea). This said, careful experimental design and a consideration for the known causes of simulator sickness can minimize the effect of simulator sickness and limit drop-out rate. VEs do not uniformly induce simulator sickness, and though Balk et al. (2013) report a 14% average drop-rate, the proportion of drop-outs ranged from 0% to 72% across studies with a 21% standard deviation. In my own study, two participants (of 59 total) failed to complete the study session due to simulator sickness (a 3.4% drop-out rate).

5. Presence

In general, presence is our sense of reality, it is the extent to which something appears to exist in the same physical world as oneself.

As Slater (2009) notes, presence is a quale, an internal and subjective experience that is difficult to define with words (e.g., describing the color blue). The difficulty in describing our experience of presence is evident, given that researchers in the field do not agree on a standard definition of presence (Table 1). The wide range of definitions is problematic, as Waterworth and Waterworth (2003a) state, "progress in understanding presence is inhibited by the fact that we are unable to agree what it is we are talking about" (p1). The issue of defining presence has prompted several researchers to publish articles exclusively focused on clarifying the term, such as Sheridan's (1992) *Defining our Terms*, Slater's (2003) *A Note on Presence Terminology*, and Lombard and Jones' (2015) *Defining Presence*. Despite these efforts, there remains no consensus.

The discrepant definitions of presence in the literature is unfortunately not an issue of semantics, but rather, different definitions often reflect fundamentally different interpretations of the phenomenon. One major issue is that, while most definitions allude to the subjective experience of reality, different authors emphasize different psychological processes in their own definitions. For example, Lombard and Ditton (1997) define presence as "the *perceptual* illusion of non-mediation" (p12, italics added), framing the experience as a perceptual process. Alternatively, Sas and O'Hare (2003) highlight cognition, defining presence as "a psychological phenomenon, through which one's *cognitive processes* are oriented toward another world" (p1, italics added). Zahorik and Jenison (1998) take a Gibsonian approach, stating that presence is "tantamount to *successfully supported action* in the environment" (p78, italics added). These examples highlight a core issue with many definitions to date, in that researchers are confounding their definition (what presence is) with a causal explanation (how presence occurs).

Another limitation with many past definitions is a tendency to regard presence, in its general sense, as an exclusively virtual (technologically mediated) experience. For example, Gorini et al. (2011) define presence as "the *technology-induced* illusion of being present in one (simulated place) when one is actually present in another (physical) place" (p99, italics added). Defining presence exclusively in technological terms ignores the experience of presence in the physical world (Steuer, 1992), as well as the shifts in presence which occur during reading (Schubert & Crusius, 2002), hallucinations (Bentall, 1990), and dream-states (Biocca, 2003). While VEs can induce an experience of reality (i.e., virtual presence) it is worth acknowledging that presence, in general, is a product of the human mind and not exclusive to a certain media.

A final limitation is that several past definitions are simply unclear. For example, Herrera et al. (2005) defines presence as the "conscious awareness of self, as both agent and experiencer, which characterizes the experiencing self of natural environments" while Spagnolli et al. (2004) defines "presence as distributed on the heterogeneous ensemble of resources that converge on action." A workable definition should be clear and this is especially true considering the existing confusion among the researchers in the field.

Acknowledging these three major limitations of past definitions, I define presence here as *the extent to which something (environment, person, object, or any other stimulus) appears to exist in the same physical world as the observer.* This working definition does not confound the description of presence with a causal process, does not refer to a technology, and offers comparatively straightforward wording.

6. Dimensions of Presence and Virtual Presence

Researchers have defined various types of presence, for example, Lombard and Jones (2015) in their review identify seven distinct types of presence. Alternatively, I argue that presence is a single construct which consists of two core dimensions: spatial presence and social presence. As I review below, these two dimensions reasonably subsume the previously defined types. I discuss these two dimensions in regard to presence in general, however, virtual presence consists of the same spatial and social dimension.

6.1. Spatial Presence

Spatial presence refers to the subjective experience that one is physically located within the environment and subject to the physical consequences therein (see Lombard & Jones, 2015). In regard to virtual presence, researchers operationalize spatial presence as the experience of visiting a place rather than viewing it on a screen (Slater, Usoh, & Steed, 1994) and often refer to the sense of "being there" in the VE (Biocca, 1997; Sas et al., 2004; Schroeder, 2002). Spatial presence is a defining feature of the VE experience and researchers note that inducing complete spatial presence, in which the VE is indistinguishably real from the physical world, is a gold standard for VE technology (Mazuryk & Gervautz, 1996; Steuer, 1992).

Other authors have suggested several additional types of presence that are reasonably subsumed by spatial presence. For example, Stevens and Jerrams-Smith (2001) define *object presence* as the subjective experience that an object exists in one's own environment; Heeter (1992) defines *environmental presence* as the degree to which the environment itself reacts to the user; while Lombard and Jones (2015) define *realism* in terms of perceptual fidelity and environment believability. However, these ostensibly different types of presence do not meaningfully differ with the underlying concept of spatial presence. The experience that an object is real ("object presence"), that the environment reacts to one's actions ("environmental presence"), and that the environment is believable ("realism"), all contribute to our feeling of being in a space.

6.2. Social Presence

Social presence refers to the degree in which another animate entity appears to co-exist in the same environment as the user (see Biocca, 1997; Heeter, 1992; Ijsselsteijn et al., 2000; Lee, 2004). The experience of social presence in a VE requires that oneself and another being are collocated in a shared space and that each entity appears to be a volitional actor (whether they are or are not). For example, one can experience a degree of social presence while interacting with a human-controlled virtual avatar or a computer-controlled virtual agent, and in fact, users apply learned social norms to both (Bailenson et al., 2004; Bailenson & Yee, 2008). Our degree of social presence can also fluctuate within the real-world, for example, those with schizophrenia may hear compellingly real voices communicating with them (Schultz et al., 2007) and those with Capgras syndrome experience that others (often close friends or family) are not real, believing that they were replaced by imposters (Edelstyn & Oyebode, 1999).

Like spatial presence, several outwardly different types of presence reasonably fall under the single dimension of social presence. For example, Lombard and Jones (2015) review *self presence*, describing how the user experiences their own virtual self-representation (i.e., their avatar) and *parapresence*, the experience that an entity is physically in one's environment when they could not logically be there. Parapresence is relatively uncommon in the presence literature, and Lombard and Jones provide examples including the experience of a phantom double and widow's attachment. Both these types of presence, self presence and parapresence, fall under social presence: the perception that one exists in a location with other volitional entities.

7. Measuring Virtual Presence

Measuring virtual presence is difficult, and to date, researchers disagree on how to best measure the phenomenon (Schuemie et al., 2001; Ijsselsteijn, Freeman, et al., 2001). Measuring virtual presence can be challenging given the traditional methodological concerns, such as limiting demand characteristics and ensuring construct validity (Van Baren & Ijsselsteijn, 2004), but virtual presence measures face several additional challenges.

First, virtual presence is an inherently subjective experience. As Slater (2009) notes, one's experience of virtual presence is not directly measurable, nor can we confirm that all people experience it in the same way. Second, it is difficult to measure shifts in virtual presence (i.e., the transition from "being in" the real world to "being in" the virtual world) because we lack the language to describe this visceral experience (see Tart, 1972). Third, there are different dimensions of virtual presence, which may be orthogonal (Skarbez et al., 2019), and so current measures may only be assessing one dimension (e.g., only spatial presence).

These challenges highlight the fact that a universally accepted and valid measure of virtual presence does not yet exist. Instead, researchers employ a wide range of measurement techniques, including behavioral, physiological, neurological, and subjective measures (Van Baren & Ijsselsteijn, 2004).

7.1. Behavioral Measures

Behavioral measures rely on the observation of a user's overt actions in a VE. Several researchers make a distinction between behavioral and task performance measures (e.g., Van Baren & Ijsselsteijn, 2004), however, task performance is ultimately an observable participant behavior and so I discuss task-performance measurements (e.g., error rate) within this category. Examples of behavioral measures include user postural stability (Freeman et al., 2000) and adherence to social norms while in the VE (Bailenson et al., 2004), as well as task completion time, error rate, and secondary task performance scores (Van Baren & Ijsselsteijn, 2004). Proponents of behavioral measures argue that, when the user experiences a strong sense of virtual presence, they behave in the virtual world as they would in the real world (Van Baren & Ijsselsteijn, 2004; Slater et al., 1996).

Behavioral measures have several advantages. First, they ostensibly limit demand characteristics, especially in comparison to self-report questionnaires (Ijsselsteijn et al., 2000). Second, many behavioral measures (e.g., postural stability) provide a continuous temporal measurement, illuminating any fluctuations in virtual presence during a VE exposure (Van Baren & Ijsselsteijn, 2004). Third, compared to physiological or neurological measures, behavioral measures are particularly practical, given that they are non-intrusive, inexpensive, and easy to implement. Fourth, researchers can employ multiple behavioral measures simultaneously. Fifth, in the case of applied VEs (e.g., a VE-based surgical trainer), a means of recording user behavior (e.g., task performance time and error rate) is often already in place.

Despite these advantages, researchers rarely employ behavioral measures in comparison to subjective measures (Van Baren & Ijsselsteijn, 2004), likely due to construct validity concerns. For example, user postural stability (a common behavioral measure in the literature) does not correlate with subjective measures of virtual presence (Freeman et al., 2000; Ijsselsteijn et al., 2002) which suggests that one or both measures lack construct validity. Further, extraneous variables may influence participant behavior independently of their virtual presence experience (Van Baren & Ijsselsteijn, 2004). For example, Freeman et al. suggest that user postural instability (i.e., swaying) does not indicate strong virtual presence but instead indicates simulator sickness, which other researchers have also suggested (Stanney et al., 1998; Stanney et al., 1999). Additionally, Nichols (1999) notes that HMD ergonomics, weight, fit, and cable length can all affect participant postural stability, which would confound postural stability as a measure of virtual presence. Behavioral measures that rely on task performance may also be susceptible to third variables; for example, the addition of stereoscopic depth cues can increase virtual presence, task performance, or both, without distinction (Sas et al., 2004; Slater & Wilbur, 1997; Waterworth & Waterworth, 2001). Further, researchers using a task-focused measure must carefully consider their experimental task given the potential for individual differences in certain tasks, such as the individual differences associated with VE navigation (Darken et al., 1996). Similarly, task-focused measures are inherently unsuitable for studies which do not include an especially active experimental task (e.g., Wallach et al., 2010).

While researchers have proposed other behavioral measures (e.g., facial expression, pointing responses, and reflex behaviors), the empirical evidence for these measures remains sparse (Van Baren & Ijsselsteijn, 2004). Researchers should further validate behavioral measures of virtual presence before considering their sole usage.

7.2. Physiological Measures

Physiological measures of virtual presence record changes in user physiology, such as fluctuations in heart-rate (Zimmons & Panter, 2003), skin conductance (Slater et al., 2009), and body temperature (Meehan et al., 2002). Advocates of these measures argue that the magnitude of physiological change in the user reflects the strength of their virtual presence experience (Meehan et al., 2002; Slater et al., 2003).

As with behavioral measures, physiological measures hold the promise of providing increased objectivity while measuring virtual presence (Van Baren & Ijsselsteijn, 2004). Physiological measures are also advantageous in that they provide a continuous temporal measurement, they are often unobtrusive to the participant, and they are especially resistant to the influence of user demand characteristics (Meehan et al., 2002; Insko, 2003).

Despite the above advantages, a major limitation of physiological measures is an apparent lack of construct validity, as evidenced through the discrepant experimental evidence. For example, while Meehan et al. (2003) report a strong correlation between participant heart-rate and self-reported virtual presence scores, other researchers report no correlation (Wiederhold et al., 1998). The validity of skin conductance measures is likewise unclear, as some authors conclude that skin conductance correlates with self-reported virtual presence scores (Wiederhold, et al., 1998; Meehan, et al., 2002), while others report no such correlation (Bailey et al., 2009). Researchers have put forth several hypotheses to explain conflicting physiological results, for instance, by suggesting the influence of orienting and defense responses (Dillon et al., 2002; Wiederhold et al., 2001) or the artifact of technical issues (Insko, 2003). Researchers should likewise consider the confound of simulator sickness, given that simulator sickness is known to induce changes in heart-rate, respiration, and skin conductance (Miller et al., 1993; Nichols et al., 1997; Strauss, 1998).

Given the range of threats to the validity of physiological measures, the underlying issue seems to be one of low construct validity. Further, though user physiology and virtual presence may appear correlated, they are typically orthogonal, just as our experience of physical reality does not necessarily invoke a strong physiological response. As both Meehan et al. (2002) and Villani et al. (2007) suggest, physiological measures may only be useful if the experimenter reasonably expects the VE to elicit a change in physiological arousal (e.g., exposing participants to a virtual precipice).

7.3. Neurological Measures

Neurological measures of virtual presence record user brain activity, using techniques such as functional magnetic resonance imaging, transcranial Doppler monitoring, and electroencephalography (Rey et al., 2008; Van Baren & Ijsselsteijn, 2004).

In addition to providing increased objectivity, neurological measures provide unique insights in the form of recorded neurological activity during a user's VE exposure (Jancke et al., 2009; Van Baren & Ijsselsteijn, 2004). For example, while using a neurological measure, Baumgartner et al. (2008) found that children and adults have different dorsolateral prefrontal cortex activity during a VE exposure, which appears to moderate the virtual presence response (Clemente et al., 2014); the dorsolateral prefrontal cortex is likely one region within a larger network of activation during virtual presence (Clemente et al., 2014; Jancke et al., 2009).

Neurological measures remain rare in virtual presence research. Contributing to this scarcity in the literature are the practical limitations common to neurological measurement, such as high overhead cost and necessary operator expertise (Mraz et al., 2003; Rey et al., 2008). Additionally, Mraz et al. (2003) note the difficulty in using an immersive display (e.g., a HMD) and measurement equipment simultaneously, for example, functional magnetic resonance imaging (fMRI) cannot operate near magnetic metals (Mraz et al., 2003) and an electroencephalogram (EEG) must be worn on the head (e.g., Kober & Neuper, 2012). Experimenters also report difficulty in interpreting neurological results, given that we know little about the brain regions specific to virtual presence (Jancke et al., 2009; Van Baren & Ijsselsteijn, 2004). Despite these challenges, it is reasonable to anticipate that the use or neurological measures will increase in the future, presuming that the technology will advance and the overhead costs will decrease.

7.4 Subjective Measures

Subjective measures of virtual presence rely on conscious feedback explicitly requested of the user. The most common subjective measure, and likely the most common presence measurement technique overall, is the post-immersion questionnaire (Van Baren & Ijsselsteijn, 2004). Post-immersion questionnaires ask the user to self-report their sense of virtual presence, often using Likert-scaled items, following their exposure to a VE (Van Baren & Ijsselsteijn, 2004).

Subjective measures of virtual presence have notable benefits. An initial advantage is that subjective measures match the internal nature of virtual presence, and because of this, many researchers argue that subjective measurement is necessary in order to gauge the experience from the user's own perspective (Fox, Bailenson, et al., 2009; Sheridan, 1992a;

Witmer & Singer, 1998). As Sheridan (1992a) states, virtual presence is "a mental manifestation, not so amenable to objective physiological definition and measurement... [therefore] subjective report is the essential basic measurement" (p3). Additionally, subjective measures, and particularly post-immersion questionnaires, are easy to administer, unobtrusive to the participant, and useful in the identification of factors during factor-analyses (Van Baren & Ijsselsteijn, 2004).

As with the above measurement categories, there are limitations to subjective measures. Subjective measures are susceptible to memory recall error and demand characteristics (Van Baren & Ijsselsteijn, 2004), can be affected by prior VE exposures (Freeman et al., 1999), and often do not detect temporal fluctuations in virtual presence (e.g., when using a post-immersion questionnaire) (Ijsselsteijn et al., 2000). An additional limitation is that several commonly used post-immersion questionnaires appear to measure separate phenomena, indicating a threat to construct validity that can critically affect the usefulness of results (Kober & Neuper, 2013; Nystad & Sebok, 2004; Usoh et al., 2000).

This said, thoughtful experimental design can mitigate several of these shortcomings. For example, careful measurement selection (e.g., avoiding measures which ask about "presence" directly) can reduce participant confusion and potential demand characteristics (Slater, 2004). Further, the experimenter can reduce the threat of participant recall error by keeping the interval between the participant's VE exposure and their questionnaire response as short as possible. Additionally, the inclusion of multiple measures, such as including multiple questionnaires or an objective corroborative measure, can provide additional confidence in questionnaire results.

8. Virtual Presence Factors

8.1. Factor Taxonomy

In a rare point of consensus in the field, researchers agree that virtual presence is a highly complex phenomenon influenced by a combination of various factors (Ijsselsteijn, Harper, et al., 2001; Jerome & Jordan, 2007; Schubert et al., 1999a; Sheridan, 1994; etc.). In this review, I categorize virtual presence factors as either *external* or *internal*, in reference to the user. External factors include the features of the VE display, such as display resolution, while internal factors include user characteristics, such as the user's immersive tendency. External factors can consist of *sensory* variables that affect the senses directly (e.g., display field-of-view), or *content* variables that affect the overarching VE theme (e.g., narrative). Internal factors can consist of *psychological* variables (e.g., locus of control), *demographic* variables (e.g., sex), or *cultural* variables (e.g., cultural background).

This taxonomy, which defines two factor categories (external; internal) and several subcategories within each, builds upon previous factor taxonomies (see Lombard et al., 2000; Sheridan, 1992; Steuer, 1992; Slater & Usoh, 2003; Witmer & Singer, 1998). First, this taxonomy clusters the known determinants of virtual presence by their underlying meaning, which is essential for accurately discussing variable groupings; in this taxonomy, *sensory* variables are simply those that affect the user's sensory system (visual immersion, auditory cues, etc.). Past researchers have not always provided clear taxonomic groups; this is most evident in Witmer and Singer's four-group taxonomy (sensory, control, distraction, and realism factors), for example, the authors include a variable *active search* (the user's ability "to control the relation of their sensors to the environment", p230) as a sensory factor, when by the definitions in their paper, this should likely be a control factor (see Witmer & Singer, 1998). Second, this framework acknowledges both external and internal factors, where many previous factor taxonomies have effectively ignored internal factors altogether (e.g., Sheridan, 1992; Steuer, 1992; Witmer & Singer, 1994). Third, the subcategories within my own taxonomy affords a greater level of specificity than previous categorizations, which have offered a limited number of general factor groupings. For example, Slater and Usoh's taxonomy distinguishes only two groups of factors (external and internal) without further subcategorization. Fourth, and because of this greater specificity, the taxonomy I use here can readily accommodate additional presence factors. As an example, again using Witmer and Singer's taxonomy as a comparison, many known factors of virtual presence (trait absorption, user sex, etc.) do not fit within their four-category taxonomy (sensory, control, distraction, and realism factors) whereas such factors readily fit within the taxonomy used here.

8.2. Discrepancies in Prior Factor Research

It is further worth noting, prior to detailing the effect of each individual variables, that the research on virtual presence factors is often contradictory. For example, researchers report that user trait extraversion is positively correlated with virtual presence (Laarni et al., 2004), negatively correlated with virtual presence (Sas, 2004), and not significantly correlated with virtual presence (Sacau et al., 2005). One can identify three likely reasons for such discrepancies: 1) third variables are affecting experimental results and limiting the comparability of results across studies, 2) past experimental results do not generalize with modern VE technology, and 3) different measures of virtual presence are measuring different underlying constructs.

Given that I discuss the research on a wide range of virtual presence factors, I provide a concise but comprehensive review below for brevity sake (Chapter 2 Sections 8.3-8.7); I include a lengthier discussion with supplementary information at the end of this paper (Appendix H). Perhaps more importantly, I acknowledged the discrepancies in past factor research while developing this study, and corresponding to the three limitations above: 1) I investigated two visual factors in a within-subjects factorial design (controlling for third variables), 2) I used a modern and commercially available HMD (so that the results are generalizable across modern technology), and 3) I used three virtual presence measures in a single study (to determine their correlation as a gauge of construct validity).

8.3. Sensory Determinants (External)

8.3.1. Visual Immersion

Visual immersion is the degree to which the VE visual display occludes the user's vision of the physical world. Draper et al. (1998) regard visual immersion as a primary determinant of virtual presence and its effect on virtual presence is well documented (Axelsson et al., 2001; Bowman & McMahon, 2007; Cummings & Bailenson, 2016; Diemer et al., 2015; Gorini et al., 2011; Hofer et al., 2020; Oschs et al., 2019; etc.). Immersive displays largely occlude the physical world, which both limits the possibility of a break in presence (Slater et al., 2003) and affords the user an egocentric perspective (Coelho et al., 2006), which further increases virtual presence (Baumgartner et al., 2008; Slater et al., 1996; Usoh & Slater, 1995; however, Gorisse et al., 2017 report a null effect of egocentric perspective on spatial presence).

8.3.2. Display Resolution

Display resolution refers to the level of visual detail provided by the visual display, whereby higher resolution displays provide finer scene acuity (Geng, 2013). Intuitively, higher visual acuity should increase virtual presence, but the effect of resolution on virtual presence is unclear, given that researchers report both significant (Duh et al., 2002) and null findings (Dinh et al., 1999). Lee (2004a) suggests that the null effect of display resolution on virtual presence is the true effect, given that the low acuity of our peripheral vision gives us a tolerance for low resolution in the periphery. Other researchers note the same, stating that, though counterintuitive, visual realism is not necessarily related to virtual presence (e.g., Nichols et al., 1999; Sanchez-Vives & Slater, 2005).

8.3.3. Field-Of-View

Field-of-view (FOV) is the range of a visual scene viewable to the user at a given time in the visual display, a value expressed in degrees of visual angle (Barfield et al., 1990). Display FOV, particularly in HMDs, is an important determinant of virtual presence (Duh et al., 2002); it is also an important factor in VE navigation (Czerwinski et al., 2002), VE distance perception (Kline & Witmer, 1996), and simulator sickness (Hettinger et al., 1987). Researchers have found that maintaining a relatively large FOV (e.g., 100˚), one roughly similar to our unmediated visual field, increases virtual presence (Alshaer et al., 2017; Duh et al., 2002; Lin et al., 2002).

8.3.4. Portrayal of Depth

Researchers agree that an accurate portrayal of depth cues in a VE is an important determinant of virtual presence (Bystrom et al., 1999; Ijsselsteijn et al., 1998). Though there is a range of visual depth cues (Cutting, 1997), the bulk of the virtual presence research focuses on the effect of stereoscopic depth cues as a factor of virtual presence (Freeman et al., 2000; Hendrix & Barfield, 1995; Ijsselsteijn et al., 2002; Ling et al., 2012; Ling et al., 2014). Additional research is necessary to understand the effect of monoscopic depth cues, and I know of a single study in this domain, which found that foreground-background cue manipulation affects the presence experience (e.g., Prothero et al., 1995).

8.3.5. Head-Tracking

Head-tracking is the change in a visual display that corresponds with changes in the location of the user. For example, when a user who is facing forward walks forward, the visual display should show objects moving past the user on either side (as occurs in the physical world). Researchers report that head-tracking, a feature especially prominent with HMDs, is critical to the experience of virtual presence (Brooks, 1999; Meehan et al., 2003). Head-tracking error can seriously degrade virtual presence and, as Brooks states in reference to virtual presence, head-tracking error is the single “greatest illusion breaker” (p18). While empirical investigations have turned off head-tracking in order to investigate its effect on task performance (e.g., Bailey & Witmer, 1994; Jackson et al., 2013; Ware et al., 1993), no known research has investigated the effect of removing head-tracking on virtual presence. The absence of this research itself speaks to the overwhelming belief that head-tracking is a prerequisite for even minimal levels of virtual presence.

8.3.6. Frame Update Rate

Frame update rate is the number of images within a timeframe (typically expressed as frames per second) that a visual display presents to the user. The perception of a seamlessly moving visual scene in a VE is the result of static images that, when displayed successively at high speeds, generate an illusion of apparent motion (Chung et al., 1989). Frame update rate is critical to maintaining the illusion of apparent motion (Nichols, 1999; Ramachandran & Anstis, 1986) and researchers suggest that the illusion requires a frame update rate of at least 25 to 30 frames-per-second (Barfield et al., 1998; Usoh & Slater, 1995; Salisbury & Srinisvasan, 1997). Multiple authors emphasize the importance of maintaining this frame update rate in order to maintain a base level of virtual presence (Barfield et al., 1998; Meehan et al., 2002).

8.3.7. Auditory Cues

Auditory cues include any sound qualities of a VE. Researchers have demonstrated that the addition of auditory cues in otherwise silent VEs increases virtual presence (Freeman & Lessiter, 2001; Poeschl et al., 2013). Further, the addition of bass increases virtual presence (Freeman & Lessiter, 2001), and binaural audio increases user virtual presence more than monaural audio cues (Hendrix & Barfield, 1995; Vastfjall, 2003). However, increasing the auditory complexity (e.g., adding audio channels) appears to have an asymptotic effect on virtual presence, in that adding additional audio channels garners a diminishing enhancement on virtual presence (Freeman & Lessiter, 2001; Hendrix & Barfield, 1995).

8.3.8. Haptic Cues

Haptic cues relate to the sense of touch, including the perception of pressure, temperature, vibration, and limb position in space (Haans & Ijsselsteijn, 2006). Research finds that allowing a user to interact physically with virtual objects and receive tactile sensory feedback increases virtual presence (Bailenson & Yee, 2008; Dinh et al., 1999; Kaul et al., 2017; Sallnas, 1999).

8.3.9. Gustatory and Olfactory Cues

Gustatory and olfactory cues relate to the human sense of taste and smell, respectively. Researchers seldom investigate gustatory and olfactory cues on virtual presence, likely because creating synthetic taste and smell cues remains a major technological challenge (Obrist et al., 2016). Additionally, the few empirical papers on these topics have conflicting results (Dinh et al., 1999; Hoffman et al., 1998; Munyan et al., 2016). The discrepant results to date, paired with evidence that the affective valiance of the stimulus may affect virtual presence ratings (Baus & Bouchard, 2017), makes it difficult to draw conclusions without further research.

8.3.10. Real World Sensory Distraction

Real-world sensory distraction refers to sensory "noise" from the physical environment, which can draw the user's limited attentional resources away from the VE and decrease presence (Slater et al., 2003). Several researchers have found that physical environment sensory distraction degrades user virtual presence (Jerome & Jordan, 2007; Nichols, 1999; Van Schaik et al., 2004; Wang et al., 2006; Witmer & Singer, 1998).

8.4. Content Determinants (External)

8.4.1. Narrative

Narrative is the story line or theme of a VE, which includes the scene appearance, character dialogue, accompanying sounds, and the appearance of virtual avatars (Slater & Wilbur, 1997). Ijsselsteijn (2003) notes the importance of narrative for virtual presence even while using high quality visual displays in that "we can be bored in VR [virtual reality] and moved to tears by a book" (p38). Researchers report that VEs with cohesive narratives tend to increase virtual presence (Gorini et al., 2011; Green et al., 2004; Slater & Wilbur, 1997). However, the narrative (e.g., a wartime battle) and the resulting user emotion (e.g., feelings of fear or excitement) appear inextricably combined. This variable coupling makes it difficult to determine which factor (narrative, user emotion, or both) causes a change in user virtual presence.

8.4.2. Environmental Realism

Environmental realism is the degree to which the VE is "plausible [and] reflects events that do or could occur in the nonmediated world" (Lombard et al., 2000, p2). Though authors in the field commonly discuss environmental realism (e.g., Robinett, 1992; Schroeder, 2002; Sutherland, 1965; Wann & Mon-Williams, 1996), I know of only two empirical studies which investigate an aspect of environmental realism on virtual presence (both related to sense of gravity), neither of which report a significant effect (Hofer et al., 2020; Slater, Usoh & Steed, 1994a).

8.4.3. Appearance of Virtual Self

VEs vary in the extent to which users can see a virtual representation of themselves (i.e., their avatar). Researchers commonly note that users place extremely high importance on their avatar (e.g., Yee & Bailenson, 2007), and further, research is emerging which indicates that avatar appearance can affect virtual presence. Specifically, abnormalities in avatar appearance (e.g., motionless eyes) can break virtual presence through an Uncanny Valley effect (see Dill et al., 2012; Mitchell et al., 2011; Mori, 1970), user avatar customization tends to increase virtual presence (Bailey et al., 2009; Ratan et al., 2007), and avatar anthropomorphization affects virtual presence; though the direction of this latter effect is unclear (Nowak & Biocca, 2003; Parise et al., 1996).

8.4.4. Social Interaction

User social interaction is an intuitively important element for virtual presence (Heeter, 1992), and researchers uniformly report that user social interaction increases virtual presence (Garau et al., 2005; Nowak & Biocca, 2003; Schubert et al., 2000). However, implementing realistic social interaction is a complex technological challenge (Biocca, 1997; Benford et al., 2001; Takemura & Kishino, 1992).

8.5. Psychological Determinants (Internal)

8.5.1. Trait Absorption

Trait absorption is a person's tendency to become fully engaged in any given task (Tellegen & Atkinson, 1974). Researchers often report that trait absorption increases virtual presence (Sas, 2004; Wirth et al., 2012) and that the variables are positively correlated ($r(36) = .36$, $p < .02$, Banos et al., 1999; $r(29) = .38$, $p < .05$ to $r(29) = .52$, $p < .01$, Kober &

Neuper, 2013; $r(239) = .19$, $p < .01$, Sacau et al., 2005; however, Murray et al., 2007 report a non-significant negative correlation, $r(63) = -.04$, $p > .05$).

8.5.2. Dissociative Tendency

Dissociation is a "sense of detachment and unreality toward oneself or the external [real] world" (Aardema et al., 2010, p429). Banos et al. (1999) and Wallach et al. (2010) regard dissociative tendency as a variable individual trait. Researchers report conflicting findings on dissociative tendency and virtual presence, indicating both a positive correlation ($r(29) = .33$, $p = .07$, Banos et al., 1999; $r(63) = .40$, $p < .01$, Murray et al., 2007) and no correlation ($r(83) = -.07$, $p > .05$, Wallach et al., 2010).

8.5.3. Immersive Tendency

Witmer and Singer (1998) conceptualize immersive tendency as the user's capacity to experience presence in an unreal world (e.g., daydreams, television, or a VE). Though one would expect a strong effect of immersive tendency on virtual presence, the relationship between the variables is unclear. Researchers investigating immersive tendency as a factor report both a positive correlation ($r(29) = 0.47$, $p < .05$, Kober & Neuper, 2013; $r(83) = 0.29$, $p < .01$, Wallach et al., 2010; multiple, Witmer & Singer, 1998) and no correlation ($r(29) = -.10$, $p > .05$, Aardema et al., 2010; $r(29) = 0.25$, $p > .05$, Kober & Neuper, 2013; $rs(36) = -.08$, $p > .05$, Krassmann et al., 2020; $r(63) = .05$, $p > .05$, Murray et al., 2007).

8.5.4. Locus of Control

Locus of control is the degree to which one attributes events as having external or internal causes (Rotter, 1966). Researchers often hypothesize that users with an external locus will experience higher virtual presence (e.g., Murray et al., 2007). However, empirical results conflict as researchers report a correlation between external locus and virtual presence ($r(63) = .22$, $p < .05$, Murray et al., 2007) and no correlation ($r(29) = -.01$, $p > .05$ to $r(29) = .18$, $p > .05$ Kober & Neuper, 2013; $r(83) = -.14$, $p > .05$, Wallach et al., 2010).

8.5.5. Personality

Personality is the combination of individual traits that define one's thoughts, emotions, and behaviors (American Psychological Association, 2018). Researchers have thus far identified several individual personality traits that appear to influence virtual presence.

Regarding the Myers Briggs (MBTI) traits, researchers have found that individuals who are more of the feeling and sensitive personality types experience increased virtual presence (Sas, 2004; Sas & O'Hare, 2003; Sas et al., 2004).

Among the OCEAN personality traits, Sacau et al. (2005) report that only agreeableness ($r(239) = .17$, $p < .01$) is significantly positively correlated with virtual presence. Sacau et al. report no significant relationship of openness ($r(239) = 0.01$, $p > .05$), conscientiousness ($r(239) = -.05$, $p > .05$), neuroticism ($r(239) = 0.05$, $p > .05$) or extraversion ($r(239) = .06$, $p > .05$). Contrary to this latter finding, Laarni et al. (2004) report a significant effect of extraversion on virtual presence; while Sas (2004) reports a significant effect of introversion on virtual presence. Further, Kober and Neuper (2013) report a significant correlation between openness and virtual presence, depending on the virtual presence measure ($r(29) = .05$, $p > .05$ to $r(29) = 0.39$, $p < .05$); Kober and Neuper do not report any other significant results for the OCEAN traits.

Laarni et al. (2004) report that trait self-forgetfulness significantly increased virtual presence and the effect of trait impulsivity on virtual presence approached significance.

The effect of trait empathy is unclear. While Sas (2004) reports a significant effect of empathy on virtual presence (whereby empathetic individuals experience increased virtual presence), Wallach et al. (2010) report no significant correlation ($r(83) = 0.18$, $p > .05$). These authors likewise report disparate findings for the effect of activity of imagination. Sas (2004) reports that activity of imagination significantly increases virtual presence while Wallach et al., report no significant correlation ($r(83) = .12$, $p > .05$). Kober and Neuper (2013) report that mental imagery ability (i.e., imagination) significantly correlates with virtual presence depending on the presence measure ($r(29) = .15$, $p > .05$ to $r(29) = .38$, $p < .05$); Iachini et al. (2019) similarly report that mental imagery ability significantly correlates with virtual presence ($r(142) = .25$, $p < .05$).

8.5.6. Mental Model Construction

A mental model is our internal representation of "seeing or perceiving landmarks... and the relationships between them" through mental imagery (Gyselinck et al., 2007, p373). For example, we have a mental model of our own neighborhood and can visualize the route from our home to the nearest grocery store. As Banos et al. (2005) state, our conscious experience is the result of such internal processing of sensory information, in which we construct a spatial representation to better understand our environment. Researchers argue that the same process occurs in a VE, in that virtual presence occurs when one can develop a cohesive mental representation of the virtual world (Banos et al., 2005; Schubert et al., 2001). Researchers generally agree that the ability to construct a mental model of the VE is an important factor in experiencing virtual presence (Alsina-Jurnet & Gutierrez-Maldonado, 2010; Sacau et al., 2005; Slater et al., 1995; Schubert & Crusius, 2002; Van Schaik et al., 2004). This said, recent empirical research suggests that objective measures of spatial ability do not predict spatial presence scores (Coxon et al., 2016), and as Coxon et al. state, additional empirical research is necessary to confirm that "spatial ability and spatial presence are linked at a broader theoretical level" (p211).

8.5.7. Attention Allocation

Attention allocation refers to the user's ability to devote attentional resources to the VE while suppressing real-world sensory distraction (Schubert et al., 2001). Many authors describe the theoretical importance of attention allocation on virtual presence (Bystrom et al., 1999; Draper et al., 1998; Freeman et al., 2000; Waterworth & Waterworth, 2001; Witmer & Singer, 1998). The importance of user attention allocation on virtual presence is indisputable; in order to consciously perceive a stimulus, one must first attend to the stimulus (Simons & Chabris, 1999). Further, Kober and Neuper (2012) provide empirical evidence for the effect of attentional allocation on virtual presence, whereby participants who devoted more attentional resources to the VE experienced increased virtual presence.

8.6. Demographic Determinants (Internal)

User demographics include those traits which allow for the differentiation of subgroups among a larger population. The research regarding demographic variables and virtual presence remains limited, though relevant evidence is emerging. For example, Van Schaik et al. (2004) report a strong negative correlation (rho = -.70, $p < .01$) between user age and virtual presence. Baumgartner et al. (2008) provide supporting evidence, finding that adults appear to critically evaluate the VE and monitor their own presence experience (with the prefrontal cortex); children (with an underdeveloped prefrontal cortex) do not, and thus, have more difficulty in inhibiting or controlling their experience of virtual presence. Liao et al. (2019) report corroborative qualitative findings, noting that child participants (aged six to eight) often spend time "testing" the realism of a VE upon exposure.

Other researchers provide discrepant results on the effect of age, for example, Felnhofer et al. (2014) report no significant effect of age on virtual presence, while Siriaraya and Ang (2012) report an effect of age only on the social dimension of virtual presence. There are several potential explanations for the contradictory findings on age and virtual presence. For example, Van Schaik et al. (2004) note that the effect of user age on virtual presence may be due to older participant's relative inexperience with VE controllers; this would make sense, as devoting attentional resources to the controller, and jerkily moving through a VE, would likely degrade virtual presence. Alternatively, Felnhofer et al. suggest that the discrepant findings could be due to broader methodological differences across studies (e.g., differences in experimental design and control of extraneous variables). Research on age as a factor of virtual presence may also benefit from a more granular delineation of age groups, as opposed to dichotomizing participants into old-young groupings (e.g., Siriaraya & Ang, 2012). Further research on user age and virtual presence is necessary prior to drawing sound conclusions.

The effect of another common demographic variable, user sex, is discussed in many aspects of VE research. Researchers report sex differences in VE navigation (Czerwinski et al., 2002; Sas, 2004; Woolley et al., 2010), VE task performance (Barfield et al., 1990), simulator sickness (Curry et al., 2020; Munafo et al., 2017; Stanney et al., 1999), and virtual presence (Lachlan & Kremar, 2011). Regarding user sex on virtual presence, the research to date suggests that men experience higher virtual presence than do women (Felnhofer et al., 2012; Lachlan & Kremar, 2011) though this difference may only apply to the spatial dimension of virtual presence (Felnhofer et al., 2014).

8.7. Cultural Determinants (Internal)

Cultural determinants relate to the user's societal upbringing, including their values, cultural norms, and religious belief. Researchers commonly speculate that cultural background is a factor of virtual presence (Banos et al., 2004; Mantovani & Riva, 1999; Pujol-Tost, 2017; Tart, 1972; Tart, 1986; Villani et al., 2012). Though user culture may impact the user's experience of a VE, such as moderating the Uncanny Valley effect (see Bartneck et al., 2007; Seyama & Nagayama, 2007), no researcher to my knowledge has directly investigated the effect of cultural background on virtual presence.

8.8. Factors in the Present Study

In the current study, I advance our knowledge of virtual presence factors by investigating the effect of environmental color and lighting quality on virtual presence. As I note above, the research on these two factors is limited. To my knowledge, only one prior study has investigated lighting quality on virtual presence (with methodological limitations; see Slater et al., 1995), and further, this will be the first study to investigate the effect of environmental color on virtual presence. This study will therefore provide novel results to the field, and it will improve our understanding of how violations of normal real-world visual cues (an absence of color or shadow) impact our sense of virtual presence.

Chapter 3: Method

1. Manipulations

I manipulated two visual factors for this study, each with two levels: environmental color (grayscale color; or full-spectrum color) and lighting quality (environmental shadows absent; environmental shadows present). These manipulations, when fully crossed, resulted in four different visual conditions.

I manipulated environmental color by depicting the same VE in grayscale (i.e., color fully desaturated) or in full-spectrum color (i.e., color fully saturated). Except for those with cone monochromacy, a remarkably rare type of colorblindness (Sharpe et al., 1999), we perceive the physical environment with color distinctions. As such, the depiction of a VE in grayscale should degrade one's experience of virtual presence.

I manipulated lighting quality by depicting the same VE with or without the depiction of environmental shadows (i.e., objects cast shadows or did not cast shadows). Environmental shadow adds sensory complexity to the visual scene and it is a visual cue that we have in the real world, as such, the absence of environmental shadows should degrade one's experience of virtual presence.

2. Primary Measures

2.1. The Presence Questionnaire (PQ v.3)

The PQ v.3 is a 29-item subjective self-report measure (focused on spatial presence) consisting of four factors: 1) involvement, 2) sensory fidelity, 3) adaptation/immersion, and 4) interface quality (Witmer et al., 2005). Witmer et al. (2005) state that the PQ v.3 is reliable across its four factors: involvement (α = .89), sensory fidelity (α = .84), adaptation/immersion (α = .84), and interface quality (α = .57). However, Van Baren and Ijsselsteijn note that the validity of the PQ (v.2) is inconclusive, as other researchers have demonstrated (e.g., Nystad & Sebok, 2004).

Researchers commonly use a version of the PQ as a measure of virtual presence (Nystad & Sebok, 2004; Vora et al., 2012; Youngblut & Huie, 2003, etc.). However, as I discuss above, researchers are using many variations of this measure (Chapter 1: Section 1). In this study, I used the full 29-item PQ v.3, but given that the authors do not provide the semantic differential scales for the items, I modified the item wording to be scored with seven-point Likert scales. The changes to item wording were subtle and faithful to the original items, for example, my modified PQ v.3 states "I was able to control events" instead of "How much were you able to control events?" (PQ v.3. Item One).

I have included the modified PQ v.3 items, as worded in this study, in Appendix I.

2.2. The Slater-Usoh-Steed (SUS) Presence Questionnaire

The SUS is a six-item subjective self-report measure (focused on spatial presence) which does not include factors (Usoh et al., 1999). The authors of the SUS do not report the reliability of their measure; the reliability of the measure is not reported in Van Baren and Ijsselsteijn's (2004) compendium and the validity of the measure is inconclusive, as other researchers have demonstrated (e.g., Nystad & Sebok, 2004).

Researchers commonly use a version of the SUS as a measure of virtual presence (Hvass et al., 2017; Norouzi et al., 2018; Zanbaka et al., 2004; etc.). However, as I discuss above, researchers are using different versions of the measure (Chapter 1: Section 1). In this study, I use the six-item SUS and treat the SUS items (scored on a seven-point Likert scale) as interval data as have others in the field (e.g., Clemente et al., 2014; Rey et al., 2008). While other researchers (e.g., Kober & Neuper, 2012; Poeschl et al., 2013) have dichotomized SUS scores to count the number of "low" and "high" items (e.g., counting items scored a six or seven as "high" virtual presence), this practice unnecessarily lowers the specificity of interval data and defines "high" scores without theoretical justification.

I have included the SUS items, as worded in this study, in Appendix I.

2.3. The Felton Presence Questionnaire (FPQ)

The FPQ is a five-item subjective self-report measure (focused on spatial presence) which does not include sub-factors. Because I will be using the FPQ for the first time, the reliability and validity of the measure are unknown.

I developed the FPQ after an evaluation of other virtual presence measurement revealed several shortcomings. As I discuss above (Chapter 1: Section 1), the FPQ has several advantages over existing measures. The FPQ operationalizes virtual presence as both "being in" the VE and "being out" of the VE. The FPQ is substantially shorter than existing measures (e.g., compared to 29-item PQ v.3). The FPQ employs more robust scoring than existing measures (e.g., compared to dichotomous SUS scoring). Finally, the FPQ does not ask participants about their experience of "presence" directly, which is both a widely known and widely ignored issue; Van Baren and Ijsselsteijn's (2004) compendium provides 20 full measures, half of which ask about "presence." Given these qualities, the FPQ has certain inherent advantages over existing subjective measures.

I have included the FPQ items, as worded in this study, in Appendix I.

3. Experimental Design

In this study, I employed a within-subjects, fully-crossed, factorial design. Given the inherently subjective nature of virtual presence, researchers note that it is advantageous to compare self-reported virtual presence scores within the same participants (e.g., Schlogl et al., 2002); there is a clear precedence of within-subjects studies in the literature (Meehan et al., 2003; Nichols et al., 1999; Park & Catrambone, 2007; Welch et al., 1996; etc.). Further, a within-subjects design increases study power and reduces necessary sample size, which was especially important given the impact of Covid-19 on the available participant sample.

In order to control for potential order effects of the conditions, I fully randomized the order of the four conditions so that each participant experienced one of 24 condition orders (four-factorial). Participants experienced each condition a single time. Likewise, I fully randomized the order of the VE starting location: there were four starting locations (in each corner of the VE, equidistant from their respective corner) and each participant experienced one of 24 starting location orders (four-factorial). Participants experienced each starting location a single time.

In order to control for potential order effects of the virtual presence measures, I counterbalanced the questionnaire order between-subjects. Each participant received the measures in one of two orders: 1) the SUS, the PQ v.3, and the FPQ, or alternatively, 2) the PQ v.3, the SUS, and the FPQ. Counterbalancing just the SUS and PQ v.3 reduced the necessary sample size (by comparing two orders and not six orders) while still advancing a primary goal of this study (a comparison of the SUS and PQ v.3).

I employed a double-blind procedure throughout this study, in which neither the research assistants (RAs), nor the participants, were aware of the study purpose. In order to further protect against demand characteristics, I included a final question in the Demographics Questionnaire which asked the participant about their knowledge of the study purpose (Appendix J: Item 11).

4. Participants

A total of 59 people participated in the study. All participants were over 18 years old and all participants had normal or corrected-to-normal vision at the time of the study. All participants completed the study only once.

I primarily recruited participants from the University of Idaho subject pool using SONA Systems: I recruited 38 of the 59 participants through SONA Systems. However, due to the impact of Covid-19, there were a limited number of participants available in the SONA Systems pool, and so I recruited an additional 21 participants through word of mouth sampling.

5. Study VE

Throughout this study, I was the primary developer of the study VE. I was primarily responsible for the VE design, programming, troubleshooting, and implementation. The study VE itself was a city, and the environment included related urban scenery: high rise buildings (of various styles), streets (with street lights, stop signs, fire hydrants, etc.), and open-air park areas (with trees, benches, statues, etc.). The study VE also included a river, which divided the environment roughly in half, and which participants could cross at one of three bridges throughout the VE.

Researchers commonly note that VE wayfinding is difficult for participants (e.g., Darken et al., 1998). In order to aid participant wayfinding, I followed Darken and Sibert's (1993) suggestions for VE design. I organized the virtual city into 16 square "blocks", indicated by roads and the transacting river. I also included various buildings (of different size, shape, and color) and different environmental features (parks, statues etc.) to act as wayfinding landmarks.

6. Experimental Task

In the study, the participant task was to navigate the VE in order to find and collect as many targets as possible within a set amount of time (four minutes). The targets were moderately sized gift boxes (approximately one cubic foot) of various colors. I placed seven targets in each of the city's 16 blocks (112 targets total). I placed each target at the ground level in the VE in nondescript locations (around corners, behind benches, etc.).

Participants primarily navigated the VE with the Vive Pro hand-held controller, which allowed them to move forward in the direction of their gaze. Participants could also move physically in the lab, which translated into VE movement, but at a limited distance given the physical space limitation.

Participants “picked-up” each target by using the Vive Pro hand-held controller. Once successfully picked-up, the target disappeared from the VE in order to provide the participant visual feedback of its acquisition. I included this task for several reasons. First, I included a task to keep the participants engaged and attentive in the VE (i.e., to reduce participant boredom or fatigue). Second, I specifically chose a visual search task to compel participants to visually explore the VE which should magnify the effect of the manipulations (environmental color and lighting quality). Third, including a study task provided a means to evaluate whether the manipulations affected a VE visual search task; though it is not a primary purpose of this study, I recorded the total number of targets that each participant found in each of the four conditions.

7. Procedure

Participants, on arriving to the lab (Student Health Center Room 014), were first greeted by the RA and given an informed consent to review and sign if they chose to participate in the study. Following this, the RA provided an intentionally general study introduction, stating that the study purpose was to better understand how people perceive virtual environments.

Following the introduction, the RA explained to the participant the goal of the experimental task (to find as many gift-boxes in the VE within a set time) and provided instructions on how to navigate the VE (by walking or by using the hand-held controller). The RA then gave the participant the HMD and hand-held controller, assisting with adjusting the HMD fit if necessary. Prior to this study, I fixed the HMD inter-screen distance at 63mm for all participants, which is the average adult inter-pupillary distance (Howarth, 1999).

When the participant was ready to begin the task, wearing both the HMD and hand-held controller, the RA started the VE software to begin the experimental trial. Once the participant was viewing the VE, the RA asked them to locate, navigate to, and pick-up a practice target (located nearby). The RA asked the participant to pick-up a set practice target at the start of all four conditions. The RA could view a mirrored desktop display throughout the study session in order to view the same display as the participant.

Following each condition, the participant completed a post-immersion questionnaire which included all three virtual presence questionnaires (Appendix I). Prior to the virtual presence measures themselves, the questionnaire began with three questions on task performance (Appendix I: Items T1-T3) which I included to obfuscate the goals of the study and reduce the potential for demand characteristics.

The study duration was approximately 45 to 60 minutes per participant.

8. Equipment

I used the HTC Vive Pro HMD, which is a stereoscopic HMD with a 110˚ field-of-view and 1440 x 1600 pixel resolution (per eye). I used the Vive Pro with a 2019 Dell Alienware 17.3" High Performance Gaming Laptop, the specifications of which exceeded the requirements to use the HTC Vive Pro HMD. The frame rate exceeded 30 frames-per-second (the threshold for apparent motion) throughout the study. I used the Unity gaming engine in conjunction with Steam VR software to design and display the study VE. All VE objects (buildings, roads, statues, trees, etc.) were freely available on the Unity Asset Store.

9. Study Management

9.1. Maximizing Participant Safety

Prior to data collection, the largest anticipated risk was the onset of participant simulator sickness, which can vary widely across studies (Balk et al. 2013). In hindsight, the effect of simulator sickness was minimal, given that the participant drop-out rate due to simulator sickness in this study (3.4%; two participants) was much lower than the 14% average (Balk et al., 2013).

Several additional safety precautions were in place due to Covid-19. Both the participant and the RA wore a face mask throughout the study and each applied hand-sanitizer upon lab entry. Following each study session (i.e., between participants) the RA sanitized the HMD, the hand-held controllers, and the lab tables.

9.2. Research Assistants

Throughout the study I managed four undergraduate RAs who assisted in the study by facilitating participant experimental sessions and entering questionnaire data. The RA's work in the study was notable. First, RA experimental facilitation, in using a double-blind procedure, mitigated the potential for experimenter bias, which is a known concern in social sciences research. Second, the combined weekly availability of the undergraduate RAs vastly increased the number of available participant slots on SONA Systems; this was especially beneficial given the limited participant pool. Third, RA data entry of questionnaire data, given that I used a double-entry procedure, minimized the risk of data entry error. Finally, the RAs were extremely helpful in offering outside perspectives on the design of the VE (e.g., in identifying VE design inconsistencies).

In addition to the above, I led weekly lab meetings with the RAs to identify any questions or concerns regarding the study.

9.3. Pilot Testing

Prior to data collection I evaluated the study through pilot testing, which led to several modifications of the VE and experimental procedure. I piloted the experiment with the help of the RAs, who recorded issues during their own practice sessions as they learned the experimental procedure (approximately ten hours of practice each, 40 hours total). Further, each RA ran me through the full study session twice prior to data collection (approximately two hours each, eight hours total). Finally, I had the assistance of additional pilot participants (fellow graduate students) who helped identify additional errors.

9.4. Institutional Review

The University of Idaho Institutional Review Board (IRB) approved all study procedures prior to data collection.

Chapter 4: Results

1. Sample Demographics

The participant sample in this study (N=59) was relatively young (*M* = 23.03, *SD* = 7.46), mostly male (57.6%; 34 of 59 participants), and primarily recruited through the University of Idaho SONA Systems (64.4%; 38 of 59 participants).

The participant sample did not use HMD technology regularly. Only two participants (3.4%) reported using a HMD weekly, both for short durations (*M* = 1.5 hours weekly).

No participant reported having color blindness.

2. Data Exclusion

Two participants did not complete the study due to simulator sickness, in both cases, the participant completed two of the four trials.

Two participants completed the same condition twice during their session due to human error and so both are missing data from one of the four conditions. In these cases, I removed the data on their second exposure to the same condition.

One participant did not have their task performance data (the number of targets found) saved on their fourth trial due to human error.

One participant did not answer the free response item regarding the study purpose.

3. Visual Manipulations on Virtual Presence (Primary Analyses)

3.1. Effect of Environmental Color and Lighting Quality

The manipulation of environmental color and lighting quality were each expected to affect virtual presence, and so I conducted a 2 (environmental color) x 2 (lighting quality) repeated-measures ANOVA to determine their effects. There was a significant main effect of color on virtual presence scores on all three virtual presence measures (Table 2). As predicted, participants reported higher virtual presence in the full-spectrum color conditions than in the grayscale conditions (Table 3; Table 4). Contrary to my prediction, there was no significant main effect of lighting quality, nor was there a significant interaction (Table 2).

4. Virtual Presence Measure Correlations (Primary Analyses)

4.1. Virtual Presence Inter-Measure Correlations

All three virtual presence measures were significantly correlated, though the strength of these correlations varied. The FPQ and SUS had the strongest correlation ($r(58) = .79$), followed by the FPQ and PQ ($r(58) = .72$) and then the SUS and PQ ($r(58) = .59$) (Table 5).

4.2. Virtual Presence Intra-Measure Correlations (Item Reliability Analysis)

Overall, all three virtual presence measures demonstrated relatively high internal consistency reliability (Table 6).

Regarding the SUS, Item 4 (Appendix I: Item S4) had the lowest item-total correlations across each of the four trials trial (respectively, $r(58) = .12$; .29; .34, and .49). This low item-total correlation is especially concerning in Trial 1, given that many virtual presence studies are between-subjects. Removing Item 4 on the SUS would increase the measure's internal consistency across trials (on average, Cronbach's α would increase from .82 to .86).

The FPQ demonstrated high internal consistency reliability. Of the FPQ items, Item 5 (Appendix I, Item F5) had the lowest item-total correlations across each trial (respectively, $r(58) = .38$; .32; .51, and .51). Removing Item 5 on the FPQ would marginally increase internal consistency reliability (on average, Cronbach's α would increase from .84 to .85).

Unlike the SUS and FPQ, which are unidimensional measures, the PQ has four subscales: involvement (12 items), sensory fidelity (6 items), adaptation/immersion (8 items) and interface quality (3 items). Three of these scales were positively correlated: involvement and sensory fidelity ($r(58) =.68$, $p < .01$), involvement and adaptation/immersion ($r(58) = .82$, $p < .01$), and sensory fidelity and adaptation/immersion ($r(58) = .40$, $p < .01$). However, the interface quality subscale was negatively correlated with involvement ($r(58) = -.46$, $p < .01$) and adaptation/immersion ($r(58) = -.47$, $p < .01$). Removing Item 17 (Appendix I: Item P17) would garner a marginal improvement to the involvement subscale (Cronbach's α would increase from .87 to .88); there are no consistent trends for individual items within the other three subfactors.

4.3 Virtual Presence Measure Stability (Test-Retest Reliability)

As a check on measure stability, I investigated the test-retest reliability of the SUS, the PQ, and the FPQ. Each demonstrated comparably high test-retest reliability, and of the measures, the PQ had the highest test-retest reliability (Table 7).

4.4 Questionnaire Order Effects

As I note in the method section above, participants completed the virtual presence measures either in Order A (PQ-SUS-FPQ) or in Order B (SUS-PQ-FPQ).

There was no significant effect of questionnaire order on SUS scores, though this effect was trending toward significance (p = .06; Table 8). Specifically, participants who completed the measures in Order A tended to report lower SUS scores (M = 4.28; SD = 0.75) than participants who completed the measures in Order B (M = 4.53; SD = .52).

There was no significant effect of questionnaire order on PQ scores (Table 8).

There was a significant effect of questionnaire order on FPQ scores (Table 8). Participants who completed the measures in Order A reported significantly lower FPQ scores (M = 3.8; SD = 1.24) than those who completed the measures in Order B (M = 4.5; SD = 1.04).

4.5 Floor and Ceiling Effects

There is no indication of a floor or ceiling effect. On average, virtual presence scores were within the middle of each measure range: SUS (M = 4.13, SD = 1.13), PQ (M = 4.4, SD = .66), and FPQ (M = 4.22; SD = 1.89).

5. Virtual Presence Covariates

5.1 Participant Characteristics

There was no significant effect of participant age, sex, or average weekly videogame playing, or recruitment method on virtual presence scores (Table 8).

5.2. *Study Characteristics*

There was no significant effect of trial number (prior exposure) or VE starting location on virtual presence scores (Table 8).

There was no significant effect of the research assistant on SUS or PQ scores, however, there was a significant effect on FPQ scores (Table 8). A post hoc analysis with Bonferroni correction revealed a significant difference ($t(25) = 2.72$, p = .01) between two of the RAs on average FPQ scores (respectively, M = 4.72, SD = 1.33; M = 3.4, SD = .86). Given that the comparison between these two RAs had small and unequal sample sizes (16 participants; 11 participants), and that the difference was not observed across measures, this effect may simply be a Type I error.

5.3 Inferred Study Purpose

As a check for potential demand characteristics, two coders independently evaluated the final free response of the Demographics Questionnaire (Appendix J: Item 11). Each participant response was coded dichotomously as “knowledgeable” or “unknowledgeable” about the true study purpose. The two coders had high inter-rater agreement, initially agreeing on 84% of the responses, before arriving at a consensus for the remainder.

There was no significant effect of participant inferred study purpose on virtual presence scores (Table 8).

6. Analyses of VE Task Performance (Targets Found)

6.1. Effect of Environmental Color and Lighting Quality

There was no significant effect of color or shadow on the number of targets found (Table 9; Table 10).

6.2. Targets Found and Virtual Presence Measure Correlations

The average number of targets found did not significantly correlate with virtual presence scores (Table 11).

6.3. Participant Characteristics

There was no significant effect of participant age, average weekly video game playing, or recruitment method, on the number of targets found (Table 10). However, there was a significant effect of participant sex on the number of targets found (Table 10), on average, men ($M = 8.6$, $SD = 1.52$) found more targets than women ($M = 6.9$, $SD = 1.84$).

6.4. *Study Characteristics*

There was a significant effect of trial number (prior exposure) on the number of targets found (Table 10). A post hoc analysis with Bonferroni correction revealed that the participants performed significantly worse in the first trial ($M = 6.83$, $SE = .37$) than all three subsequent trials (respectively, $M = 8.40$, $SD = .31$; $M = 8.61$, $SE = .29$; $M = 8.37$, $SE = .26$). No other significant pairwise comparisons were observed.

There was a significant effect of starting location on the number of targets found (Table 10). A post hoc analysis with Bonferroni correction revealed a significant difference ($t(54) = -4.14$, $p < .01$) between two VE starting locations on the number of targets found. Participants found more targets when they started in the bottom-right ($M = 8.7$, $SE = .36$) than when starting in the top-left ($M = 7.4$, $SE = .86$). This effect appears to be due to my own placement of the virtual targets, as two targets near the bottom-right starting location are particularly close. No other significant pairwise comparisons were observed.

There was no significant effect of the research assistant on the average number of targets found (Table 10).

6.5 Inferred Study Purpose

There was no significant effect of participant inferred study purpose on the number of targets found (Table 10).

Chapter 5: Discussion

1. Introduction

This study had two primary purposes: to explore the effect of two visual factors on virtual presence and to determine if the results of three virtual presence measures correlate (indicating convergent validity). I first discuss the study results as it relates to these two primary goals. I then discuss secondary findings, identify study limitations, and provide future research directions.

2. Implication of Primary Analyses: Environmental Color and Lighting Quality

Regarding the effect of the two visual factors, the results indicate that environment color significantly affects virtual presence while lighting quality does not. Considering how many factors influence virtual presence, the observed effect size of environmental color across the virtual presence measures is fairly sizable, explaining approximately 20 to 30% of the variance in this experiment. The null effect of lighting quality, on the other hand, is counter to expectations. Though I anticipated a smaller effect of lighting quality, the effect size of this variable across measures was lower than expected, explaining 3 to 5% of the variance. Despite this latter null result, both findings advance our theoretical and applied knowledge of virtual presence factors.

First, this study was the first to empirically investigate the effect of environmental color, and this study provided a much stronger investigation of lighting quality than the one study available until now. Slater et al.'s (1995) study on lighting quality, in which they report that shadow significantly increases virtual presence, has some important limitations. Slater et al. recruited a small sample size (eight participants) of their colleagues, used a low-resolution display (340 x 240 pixels) with a restricted field-of-view (75˚) and low frame rate (six to eight frames per second), and they report an unusually complex statistical analysis for the data collected. The null result in the present study is likely closer to the true effect of lighting quality than Slater et al.'s prior work.

Beyond the inherent importance of investigating these factors of virtual presence, which advances our academic understanding of virtual presence, these results have applied importance. Environmental color and lighting quality are truly manipulable variables, in that a wide range of VE content-creators, who have an interest in enhancing presence (e.g., developers, trainers, researchers, etc.,) can easily leverage these two factors. This is contrast to the research on other visual factors, which are manipulable in theory, but not manipulable in practice (e.g., display resolution). Identifying the effect size of manipulable factors, regardless of the magnitude of the effect, always has applied importance. By reporting effect sizes, VE content-creators can use the results to decide the benefit of incorporating a certain factor (e.g., lighting quality on virtual presence or task performance) against the cost of its implementation (e.g., its fiscal and computational cost).

3. Implication of Primary Analyses: Measure Convergence

The SUS, the PQ v.3, and the FPQ are all significantly correlated, and so overall, they exhibit convergent validity. In short, given that third variables were controlled in this within-subjects study, the results indicate that all three measures are gauging the same underlying construct. This is a promising result. Researchers have been using the SUS and PQ for decades and evidence of their *divergence,* especially diveregence when using the latest version of the PQ, would imply that a bulk of existing research is invalid; this still may be the case, and further measure validation is needed, but this result is encouraging. The low inter-measure correlations between the SUS and PQ observed in some prior research (e.g., Nystad & Sebok, 2004; Usoh et al., 2000) may be due to the inconsistent application of these measures across prior studies. This study, in using the full quantitative SUS and full PQ v.3, and by accounting for (what was a significant) order effect, provides a more accurate understanding of the measure convergence. This said, among the virtual presence measures, the SUS-PQ correlation was the lowest and so additional modifications to the SUS or PQ may be necessary. Future research would benefit from completing further analysis on the factor structure of the PQ, the SUS, or a factor analysis on a combined SUS-PQ; a combined measure may be better than either one individually.

In addition to the above, this first investigation of the FPQ garnered encouraging results. As I discuss above (Chapter 1: Section 1) the FPQ offers several advantages over existing measures of spatial presence and it may be a useful alternative to existing measures. This study demonstrates that the FPQ correlates with both the SUS and the PQ, and the FPQ-SUS and FPQ-PQ correlations were substantially stronger than the SUS-PQ correlation. The FPQ also demonstrated high internal consistency reliability across each trial, in many cases, higher than those of the SUS or the PQ. The effect of the number of items on internal consistency reliability should also be taken into consideration, in that the internal consistency reliability of the FPQ (5-items) is nearly the same as the that of the involvement sub-factor of the PQ (12-items). The FPQ also demonstrated its stability across trials, given that its test-retest reliability was high, and comparable to that of the SUS and PQ. These analyses of reliability, paired with its convergence to the SUS and PQ, provide early evidence supporting the viability of the FPQ in virtual presence research. These results are especially encouraging given that this was the first ever study to use the FPQ; the measure has not undergone any analysis to identify modifications and strengthen its reliability (as done with the PQ v.3). This is not to say that the FPQ does not need modification and further testing, but rather, that the FPQ may genuinely be advantageous for virtual presence measurement in the future.

4. Study Limitations

First, while this study provides evidence for the convergent validity of the SUS, PQ v.3, and the FPQ, the overall construct validity of each of these measures remains uncertain. In other words, the three measures appear to measure the same phenomenon, which we believe is virtual presence, but exactly what is being measured is still not clear. Including a test of discriminant validity (e.g., comparing measure results across display types) or including an objective corroborative measure (e.g., a behavioral measure in the VE) would provide further validation for these measures.

Second, while the investigation of participant demographic variables (let alone cultural background) is an area ripe with research potential, the results of participant demographics in this study was limited given the limited variability in the sample. As such, the results of certain demographic covariates (e.g., participant age) should be taken with some caution.

Third, the overall fidelity of the VE may have affected the results of the lighting quality manipulation. While the quality of the VE in this study is surely higher quality than many prior studies, a question arises regarding if the relatively low fidelity VE (which I developed myself) is masking the more subtle effect of lighting quality. Perhaps the absence of shadow would have had a magnified effect on virtual presence if the surrounding VE was of higher sensory quality.

5. Future Directions

A future research direction, as I note in the limitation section just above, is to investigate whether the effect of environmental color and lighting quality remains consistent in an otherwise high-fidelity VE, or if these effects are magnified. In a general sense, research investigating the effect of the VE "base fidelity" as a manipulation would inform all other virtual presence studies, as the effect of any single VE manipulation may ultimately depend on its deviation from the VE's overall fidelity.

Future researchers should also continue investigating the levels within "known" virtual presence factors. For example, researchers cite environmental realism as an important factor of virtual presence, and despite the fact realism can be investigated in numerous ways, only two researchers have investigated its effect using very similar manipulations. The same opportunity is true with many factors, as currently, our knowledge of most factors is based on a limited number of studies which look at only two levels.

Researchers should also update the existing research on virtual presence factors with modern VE technology. I outline the limitations of Slater et al.'s (1995) work on lighting quality in this study given its particular relevance to the research, but similar limitations are observable in other past research. The research on presence factors conducted with past HMD technologies (e.g., in the early 1990s) is susceptible to Type II errors (falsely null results) given that the technology often had known "illusion breakers" of presence, such as low frame rate and high head tracking latency.

Researchers should also make greater use of factorial designs to detect factor interactions. For example, it is reasonable to assume that a strong VE narrative will have a large effect in a low-fidelity display and a muted effect in a high-fidelity display. Another ample source of potential interactions would be to investigate how internal variables (e.g., dissociative tendency) interact with external variables (e.g., display fidelity). Detecting such interactions would be theoretically and practically important, and further, given the limited use of factorial designs, this direction offers abundant research opportunities.

Given the complexity of presence as a construct, there are many factors that have not yet been investigated whatsoever (e.g., drug intoxication, user culture, user stress level, VE sensory-conflict, etc.). The exploration of these novel factors could be especially useful if guided by an underlying framework (e.g., to test a theory of presence) or if intended to enhance the growing VE industry (e.g., to determine which manipulable factors most enhance virtual presence in a VE trainer).

Future researchers would benefit from the creation of a compedium of virtual presence factors. An effective factor compendium would employ a comprehensive taxonomy, which would be necessary to efficiently incorporate the wide, and still widening, range of potential virtual presence factors. Further, a compendium of factors should incorporate both significant and null results; publishing null results is necessary to avoid the unnecessary replication of results, and given the applied importance of virtual presence, VE content-creators would benefit from knowing which factors increase virtual presence and which factors do not.

Regarding measurement, this field lacks a reliable and valid measure of virtual presence. Future research should continue evaluating virtual presence measures, because as of now, we are unsure about what it is that we are measuring. Future research should seek to further validate a measure of presence in general, for example, a valid measure should be able to reliably discriminate between presence in a low fidelity VE, presence in a high fidelity VE, and presence in the real world. Beyond the subjective measurement of virtual presence, no objective measure exists which can reliably and accurately measure virtual presence. As with subjective measures, researchers are reporting the results of studies using behavioral, physiological, and neurological measures without clear evidence for their construct validity.

While my study advanced our understanding on the factors of virtual presence and its measurement, substantial additional research is necessary for us to understand the factors of virtual presence and its measurement.

References

Aardema, F., O'Connor, K., Cote, S., & Taillon, A. (2010). Virtual reality induces dissociation and lowers sense of presence in objective reality. *Cyberpsychology, Behavior, and Social Networking*, *13*(4), 429-435.

Alaraj, A., Lemole, M., Finkle, J., Yudkowsky, R., Wallace, A., Luciano, C., ... & Charbel, F. (2011). Virtual reality training in neurosurgery: review of current status and future applications. *Surgical neurology international*, *2*.

Alcaniz, M., Banos, R., Botella, C., & Rey, B. (2003). The EMMA project: emotions as a determinant of presence. *PsychNology Journal*, *1*(2), 141-150.

Alexander, A., Brunyee, T., Sidman, J., & Weil, S. (2005). From gaming to training: A review of studies on fidelity, immersion, presence, and buy-in and their effects on transfer in pc-based simulations and games. *DARWARS Training Impact Group*, *5*, 1-14.

Allison, D., Wills, B., Bowman, D., Wineman, J., & Hodges, L. (1997). The virtual reality gorilla exhibit. *IEEE Computer Graphics and Applications*, *17*(6), 30-38.

Alshaer, A., Regenbrecht, H., & O'Hare, D. (2017). Immersion factors affecting perception and behaviour in a virtual reality power wheelchair simulator. *Applied ergonomics*, *58*, 1-12.

Alsina-Jurnet, I., & Gutierrez-Maldonado, J. (2010). Influence of personality and individual abilities on the sense of presence experienced in anxiety triggering VEs. *International journal of human-computer studies*, *68*(10), 788-801.

Alsina-Jurnet, I., Carvallo-Beciu, C., & Gutieerrez-Maldonado, J. (2007). Validity of virtual reality as a method of exposure in the treatment of test anxiety. *Behavior Research Methods*, *39*(4), 844-851.

Alsina-Jurnet, I., Gutierrez-Maldonado, J., & Rangel-Gomez, M. (2011). The role of presence in the level of anxiety experienced in clinical VEs. *Computers in Human Behavior*, *27*(1), 504-512.

American Psychological Association. (2018). Personality. Retrieved from https://www.apa.org/topics/personality/

Anderson, C. Shibuya, A., Ihori, N., Swing, E., Bushman, B., Sakamoto, A., ... & Saleem, M. (2010). Violent video game effects on aggression, empathy, and prosocial behavior in Eastern and Western countries: A meta-analytic review. *Psychological bulletin*, *136*(2), 151.

Anderson, M., McKay, M., & Willis, W. (1997). *The VirtualwindoW for nuclear applications* (No. INEL/CON-97-00455; CONF-970464-). Idaho National Engineering Lab., Idaho Falls, ID (United States).

Ausburn, L. J., Martens, J., Baukal Jr, C. E., Agnew, I., Dionne, R., & Ausburn, F. B. (2019). User Characteristics, Trait vs. State Immersion, and Presence in a First-Person Virtual World. *Journal For Virtual Worlds Research*, *12*(3).

Axelsson, A., Abelin, A., Heldal, I., Schroeder, R., & Widestrom, J. (2001). Cubes in the cube: A comparison of a puzzle-solving task in a virtual and a real environment. *CyberPsychology & Behavior*, *4*(2), 279-286.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE computer graphics and applications*, *21*(6), 34-47.

Bailenson, J., & Yee, N. (2008). Virtual interpersonal touch: Haptic interaction and copresence in collaborative VEs. *Multimedia Tools and Applications*, *37*(1), 5-14.

Bailenson, J., Aharoni, E., Beall, A., Guadagno, R., Dimov, A., & Blascovich, J. (2004, October). Comparing behavioral and self-report measures of embodied agents' social presence in immersive VEs. In *Proceedings of the 7th Annual International Workshop on PRESENCE* (pp. 1864-1105).

Bailenson, J., Beall, A., Blascovich, J., Raimundo, M., & Weisbuch, M. (2001, September). Intelligent agents who wear your face: Users' reactions to the virtual self. In *International Workshop on Intelligent Virtual Agents* (pp. 86-99). Springer, Berlin, Heidelberg.

Bailey, J., & Witmer, B. (1994, October). Learning and transfer of spatial knowledge in a virtual environment. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 38, No. 18, pp. 1158-1162). Sage CA: Los Angeles, CA: SAGE Publications.

Bailey, R., Wise, K., & Bolls, P. (2009). How avatar customizability affects children's arousal and subjective presence during junk food–sponsored online video games. *CyberPsychology & Behavior*, *12*(3), 277-283.

Balk, S., Bertola, M., & Inman, V. (2013). Simulator sickness questionnaire: twenty years later.

Banos, R., Botella, C., Alcaniz, M., Liano, V., Guerrero, B., & Rey, B. (2004). Immersion and emotion: their impact on the sense of presence. *Cyberpsychology & behavior*, *7*(6), 734-741.

Banos, R., Botella, C., Garcia-Palacios, A., Villa, H., Perpina, C., & Gallardo, M. (1999). Psychological variables and reality judgment in VEs: the roles of absorption and dissociation. *CyberPsychology & Behavior*, *2*(2), 143-148.

Banos, R., Botella, C., Guerrero, B., Liano, V., Raya, M., & Rey, B. (2005). The Third Pole of the Sense of Presence: Comparing Virtual and Imagery Spaces. *PsychNology Journal*, *3*(1), 90-100.

Barfield, W., Baird, K., & Bjorneseth, O. (1998). Presence in VEs as a function of type of input device and display update rate. *Displays*, *19*(2), 91-98.

Barfield, W., Hendrix, C., & Bystrom, K. (1999). Effects of stereopsis and head-tracking on performance using desktop VE displays. *Presence: Teleoperators & VEs*, *8*(2), 237-240.

Barfield, W., Lim, R., & Rosenberg, C. (1990, October). Visual enhancements and geometric field of view as factors in the design of a three-dimensional perspective display. In *Proceedings of the Human Factors Society Annual Meeting* (Vol. 34, No. 19, pp. 1470-1473). Sage CA: Los Angeles, CA: SAGE Publications.

Bartneck, C., Kanda, T., Ishiguro, H., & Hagita, N. (2007, August). Is the uncanny valley an uncanny cliff?. In *The 16th IEEE International Symposium on Robot and Human Interactive Communication* (pp. 368-373). IEEE.

Baumgartner, T., Speck, D., Wettstein, D., Masnari, O., Beeli, G., & Jancke, L. (2008). Feeling present in arousing virtual reality worlds: prefrontal brain regions differentially orchestrate presence experience in adults and children. *Frontiers in human neuroscience*, *2*, 8.

Baus, O., & Bouchard, S. (2017). Exposure to an unpleasant odour increases the sense of presence in virtual reality. *Virtual Reality*, *21*(2), 59-74.

Bayon, V., Wilson, J., Stanton, D., & Boltman, A. (2003). Mixed reality storytelling environments. *Virtual Reality*, *7*(1), 54-63.

Beardon, C. (1992). The ethics of virtual reality - Sussex. *Digital Creativity (Intelligent Tutoring Media)*, *3*(1), 23-28.

Benford, S., Bowers, J., Fahleen, L. E., Greenhalgh, C., & Snowdon, D. (1995, May). User embodiment in collaborative VEs. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 242-249). ACM Press/Addison-Wesley Publishing Company.

Benford, S., Greenhalgh, C., Rodden, T., & Pycock, J. (2001). Collaborative VEs. *Communications of the ACM*, *44*(7), 79-85.

Bentall, R. (1990). The illusion of reality: a review and integration of psychological research on hallucinations. *Psychological bulletin*, *107*(1), 82.

Bergstrom, I., Azevedo, S., Papiotis, P., Saldanha, N., & Slater, M. (2017). The plausibility of a string quartet performance in virtual reality. *IEEE transactions on visualization and computer graphics*, *23*(4), 1352-1359.

Biocca, F. (1997). The cyborg's dilemma: Progressive embodiment in VEs. *Journal of computer-mediated communication*, *3*(2), JCMC324.

Biocca, F. (2003, May). Can we resolve the book, the physical reality, and the dream state problems? From the two-pole to a three-pole model of shifts in presence. In *EU Future and Emerging Technologies, Presence Initiative Meeting*.

Biocca, F., & Levy, M. (1995). *Communication in the age of virtual reality*. Routledge.

Boletsis, C. (2017). The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction*, *1*(4), 24.

Botella, C., Fernandez-Alvarez, J., Guillen, V., Garcia-Palacios, A., & Banos, R. (2017). Recent progress in virtual reality exposure therapy for phobias: a systematic review. *Current psychiatry reports*, *19*(7), 42.

Botvinick, M., & Cohen, J. (1998). Rubber hands ‘feel’ touch that eyes see. *Nature*, *391*(6669), 756.

Boud, A., Baber, C., & Steiner, S. (2000). Virtual reality: A tool for assembly?. *Presence: Teleoperators & VEs*, *9*(5), 486-496.

Bowman, D. (1999). Interaction techniques for immersive VEs: Design, evaluation, and application. *Journal of Visual Languages and Computing*, *10*, 37-53.

Bowman, D., & McMahan, R. (2007). Virtual reality: how much immersion is enough?. *Computer*, *40*(7).

Bowman, D., Kruijff, E., LaViola Jr, J., & Poupyrev, I. (2001). An introduction to 3-D user interface design. *Presence: Teleoperators & Virtual Environments*, *10*(1), 96-108.

Bown, J., White, E., & Boopalan, A. (2017). Looking for the ultimate display: A brief history of virtual reality. In *Boundaries of Self and Reality Online* (pp. 239-259). Academic Press.

Boyer, P. (1963). Boston Book Censorship in the Twenties. *American Quarterly*, *15*(1), 3-24.

Brelsford, J. (1993, October). Physics education in a VE. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 37, No. 18, pp. 1286-1290). Sage CA: Los Angeles, CA: SAGE Publications.

Brewster, D. (1856). *The Stereoscope; Its History, Theory and Construction, with Its Application to the Fine and Useful Arts and to Education, Etc*. John Murray.

Brey, P. (2008). Virtual reality and computer simulation. In *Ethics and emerging technologies* (pp. 315-332). Palgrave Macmillan, London.

Briggs, K. (1976). *Myers-Briggs type indicator*. Palo Alto, CA: Consulting Psychologists Press.

Brooks, F. (1999). What's real about virtual reality?. *IEEE Computer graphics and applications*, *19*(6), 16-27.

Buchleitner, J. (2018, April 20). *When virtual reality feels real, so does the sexual harassment.* Retrieved from https://www.salon.com/2018/04/21/when-virtual-reality-feels-real-so-does-the-sexual-harassment_partner/

Buxton, B., & Fitzmaurice, G. (1998). HMDs, caves & chameleon: a human-centric analysis of interaction in virtual space. *ACM SIGGRAPH Computer Graphics*, *32*(4), 69-74.

Bystrom, K., Barfield, W., & Hendrix, C. (1999). A conceptual model of the sense of presence in VEs. *Presence: Teleoperators & VEs*, *8*(2), 241-244.

Calvert, S., & Tan, S. (1994). Impact of virtual reality on young adults' physiological arousal and aggressive thoughts: Interaction versus observation. *Journal of applied developmental psychology*, *15*(1), 125-139.

Carlin, A., Hoffman, H., & Weghorst, S. (1997). Virtual reality and tactile augmentation in the treatment of spider phobia: a case report. *Behaviour research and therapy*, *35*(2), 153-158.

Carretta, T., & Dunlap, R. (1998). *Transfer of Training Effectiveness in Flight Simulation: 1986 to 1997*. Air Force Research Lab Brooks AFB TX Human Effectiveness Directorate.

Castronova, E. (2001). Virtual worlds: A first-hand account of market and society on the cyberian frontier.

Centers for Disease Control. *Drug Overdose Overview.* (2019, August 13). Retrieved from https://www.cdc.gov/drugoverdose/data/prescribing/overview.html

Chang, H. (2009, April 13). *Simulators always valuable in military training.* Retrieved from: www.army.mil/article/19599/simulators_always_valuable_in_military_training

Chung, J., Harris, M., Brooks, F., Fuchs, H., Kelley, M., Hughes, J., ... & Pique, M. (1989, September). Exploring virtual worlds with head-mounted displays. In *Three-Dimensional Visualization and Display Technologies* (Vol. 1083, pp. 42-53). International Society for Optics and Photonics.

Churchill, E., & Snowdon, D. (1998). Collaborative VEs: an introductory review of issues and systems. *Virtual Reality*, *3*(1), 3-15.

Clemente, M., Rodriguez, A., Rey, B., & Alcaniz, M. (2014). Assessment of the influence of navigation control and screen size on the sense of presence in virtual reality using EEG. *Expert Systems with Applications*, *41*(4), 1584-1592.

Cobb, S., D'Cruz, M., & Wilson, J. (1995). Integrated manufacture: A role for virtual reality?. *International Journal of Industrial Ergonomics*, *16*(4-6), 411-425.

Coelho, C., Tichon, J., Hine, T., Wallis, G., & Riva, G. (2006). Media presence and inner presence: the sense of presence in virtual reality technologies. In *From communication to presence: Cognition, emotions and culture towards the ultimate communicative experience* (pp. 25-45). IOS Press, Amsterdam.

Cole, H., & Griffiths, M. (2007). Social interactions in massively multiplayer online role-playing gamers. *Cyberpsychology & behavior*, *10*(4), 575-583.

Coxon, M., Kelly, N., & Page, S. (2016). Individual differences in virtual reality: Are spatial presence and spatial ability linked?. *Virtual Reality*, *20*(4), 203-212.

Cruz-Neira, C., Sandin, D., & DeFanti, T. (1993, September). Surround-screen projection-based virtual reality: the design and implementation of the CAVE. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques* (pp. 135-142).

Cruz-Neira, C., Sandin, D., DeFanti, T., Kenyon, R., & Hart, J. (1992). The CAVE: audio visual experience automatic virtual environment. *Communications of the ACM*, *35*(6), 64-73.

Cruz, A., Paredes, H., Fonseca, B., Morgado, L., & Martins, P. (2014). Can presence improve collaboration in 3D virtual worlds?. *Procedia Technology*, *13*, 47-55.

Curry, C., Li, R., Peterson, N., & Stoffregen, T. (2020). Cybersickness in virtual reality head-mounted displays: examining the influence of sex differences and vehicle control. *International Journal of Human–Computer Interaction*, *36*(12), 1161-1167.

Cutting, J. (1997). How the eye measures reality and virtual reality. *Behavior Research Methods, Instruments, & Computers*, *29*(1), 27-36.

Cutting, J., & Vishton, P. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of space and motion* (pp. 69-117).

Czernuszenko, M., Pape, D., Sandin, D., DeFanti, T., Dawe, G., & Brown, M. (1997). The ImmersaDesk and Infinity Wall projection-based virtual reality displays. *ACM SIGGRAPH Computer Graphics*, *31*(2), 46-49.

Czerwinski, M., Tan, D., & Robertson, G. (2002, April). Women take a wider view. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 195-202). ACM.

Darken, R., Allard, T., & Achille, L. (1998). Spatial orientation and wayfinding in large-scale virtual spaces: An introduction. *Presence*, *7*(2), 101-107.

Darken, R., Cockayne, W., & Carmein, D. (1997, October). The omni-directional treadmill: a locomotion device for virtual worlds. In *Proceedings of the 10th annual ACM symposium on User interface software and technology* (pp. 213-221). ACM.

Darken, R., & Sibert, J. (1993, December). A toolset for navigation in virtual environments. In *Proceedings of the 6th annual ACM symposium on User interface software and technology* (pp. 157-165).

Das, R. (2018, May 31). Virtual reality: The alternative to marijuana and opioids for pain management. Retrieved from https://www.forbes.com/sites/reenitadas/2018/05/31/virtual-reality-the-alternative-to-marijuana-and-opioids-for-pain-management/#240aaf0f51d6

Dascal, J., Reid, M., Ishak, W., Spiegel, B., Recacho, J., Rosen, B., & Danovitch, I. (2017). Virtual reality and medical inpatients: A systematic review of randomized, controlled trials. *Innovations in clinical neuroscience*, *14*(1-2), 14.

De Angelo, J. (2000). The Link Flight Trainer: A Historic Mechanical Engineering Landmark, Roberson Museum and Science Center, Binghamton, New York, June 10, 2000.

De-Sola Gutierrez, J., Rodriguez de Fonseca, F., & Rubio, G. (2016). Cell-phone addiction: A review. *Frontiers in psychiatry*, 7, 175.

Deering, M. (1992). High resolution virtual reality. *ACM SIGGRAPH Computer Graphics*, *26*(2), 195-202.

Dibbell, J. (2003, January 1). *The Unreal Estate Boom*. Retrieved from https://www.wired.com/2003/01/gaming-2/

Dill, K., & Dill, J. (1998). Video game violence: A review of the empirical literature. *Aggression and violent behavior*, *3*(4), 407-428.

Dill, V., Flach, L., Hocevar, R., Lykawka, C., Musse, S., & Pinho, M. (2012, September). Evaluation of the uncanny valley in CG characters. In *International Conference on Intelligent Virtual Agents* (pp. 511-513). Springer, Berlin, Heidelberg.

Dillon, C., Keogh, E., & Freeman, J. (2002). It's been emotional': Affect, physiology, and presence. *Proceedings of Presence*, 223-232.

Dinh, H., Walker, N., Hodges, L., Song, C., & Kobayashi, A. (1999, March). Evaluating the importance of multi-sensory input on memory and the sense of presence in VEs. In *Proceedings IEEE Virtual Reality (Cat. No. 99CB36316)* (pp. 222-228). IEEE.

DiZio, P., & Lackner, J. (1997). Circumventing side effects of immersive virtual environments. *Advances in human factors/ergonomics*, *21*, 893-896.

Draper, J., Kaber, D., & Usher, J. (1998). Telepresence. *Human factors*, *40*(3), 354-375.

Draper, J., Kaber, D., & Usher, J. (1999). Speculations on the value of telepresence. *CyberPsychology & Behavior*, *2*(4), 349-362.

Drascic, D., & Milgram, P. (1996, April). Perceptual issues in augmented reality. In *Stereoscopic displays and virtual reality systems III* (Vol. 2653, pp. 123-135). International Society for Optics and Photonics.

Duh, H., Lin, J., Kenyon, R., Parker, D., & Furness, T. (2002). Effects of characteristics of image quality in an immersive environment. *Presence: Teleoperators & VEs*, *11*(3), 324-332.

Durlach, N. (1997). The potential of teleoperation for entertainment and education. *Presence: Teleoperators & VEs*, *6*(3), 350-351.

Edelstyn, N., & Oyebode, F. (1999). A review of the phenomenology and cognitive neuropsychological origins of the Capgras syndrome. *International Journal of Geriatric Psychiatry*, *14*(1), 48-59.

Ehrsson, H. (2007). The experimental induction of out-of-body experiences. *Science*, *317*(5841), 1048-1048.

Ellis, S. (1991). Nature and origins of VEs: a bibliographical essay. *Computing systems in engineering*, *2*(4), 321-347.

Ellis, S. (1996). Presence of mind: A reaction to Thomas Sheridan's "further musings on the psychophysics of presence". *Presence: Teleoperators & VEs*, *5*(2), 247-259.

Ellis, S., Young, M., Adelstein, B., & Ehrlich, S. (1999, September). Discrimination of changes of latency during voluntary hand movement of virtual objects. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 43, No. 22, pp. 1182-1186). Sage CA: Los Angeles, CA: SAGE Publications.

Emmelkamp, P., Krijn, M., Hulsbosch, A., De Vries, S., Schuemie, M., & van der Mast, C. (2002). Virtual reality treatment versus exposure in vivo: a comparative evaluation in acrophobia. *Behaviour research and therapy*, *40*(5), 509-516.

Entertainment Software Association. (2017). *2017 Sales, demographic and usage data: Essential facts about the computer and video game industry*. Retrieved from http://www.theesa.com/wp-content/uploads/2017/09/EF2017_Design_FinalDigital.pdf

Estes, A. (2013, December 03). Some Good Things Drones Can (Actually) Do. Retrieved from https://gizmodo.com/some-good-things-drones-can-actually-do-1475717696

Faccio, M., & McConnell, J. (2018). *Death by Pokemon GO: The Economic and Human Cost of Using Apps While Driving* (No. w24308). National Bureau of Economic Research.

Fairchild, K., Lee, B., Loo, J., & Serra, L. (1993, September). The heaven and earth virtual reality: Designing applications for novice users. In *Proceedings of IEEE virtual reality annual international symposium* (pp. 47-53). IEEE.

Felnhofer, A., Kothgassner, O., Beutl, L., Hlavacs, H., & Kryspin-Exner, I. (2012). Is virtual reality made for men only? Exploring gender differences in the sense of presence. *Proceedings of the International Society on presence research*, 103-112.

Felnhofer, A., Kothgassner, O., Hauk, N., Beutl, L., Hlavacs, H., & Kryspin-Exner, I. (2014). Physical and social presence in collaborative virtual environments: Exploring age and gender differences with respect to empathy. *Computers in Human Behavior*, *31*, 272-279.

Ferguson, C. (2007). The good, the bad and the ugly: A meta-analytic review of positive and negative effects of violent video games. *Psychiatric Quarterly*, *78*(4), 309-316.

Ferguson, C. (2010). Blazing angels or resident evil? Can violent video games be a force for good?. *Review of general psychology*, *14*(2), 68.

Flynn, D., Van Schaik, P., Blackman, T., Femcott, C., Hobbs, B., & Calderon, C. (2003). Developing a virtual reality–based methodology for people with dementia: a feasibility study. *CyberPsychology & Behavior*, *6*(6), 591-611.

Fox, J., Arena, D., & Bailenson, J. (2009). Virtual reality: A survival guide for the social scientist. *Journal of Media Psychology*, *21*(3), 95-113.

Fox, J., Bailenson, J., & Binney, J. (2009). Virtual experiences, physical behaviors: The effect of presence on imitation of an eating avatar. *Presence: Teleoperators and VEs*, *18*(4), 294-303.

Freeman, D., Slater, M., Bebbington, P., Garety, P., Kuipers, E., Fowler, D., ... & Vinayagamoorthy, V. (2003). Can virtual reality be used to investigate persecutory ideation?. *The Journal of nervous and mental disease*, *191*(8), 509-514.

Freeman, J., & Lessiter, J. (2001). Here, there and everywhere: the effects of multichannel audio on presence. Georgia Institute of Technology.

Freeman, J., Avons, S., Meddis, R., Pearson, D., & IJsselsteijn, W. (2000). Using behavioral realism to estimate presence: A study of the utility of postural responses to motion stimuli. *Presence: Teleoperators & VEs*, *9*(2), 149-164.

Freeman, J., Avons, S., Pearson, D., & IJsselsteijn, W. (1999). Effects of sensory information and prior experience on direct subjective ratings of presence. *Presence: Teleoperators & VEs*, *8*(1), 1-13.

Freina, L., & Ott, M. (2015, April). A literature review on immersive virtual reality in education: state of the art and perspectives. In *The international scientific conference elearning and software for education* (Vol. 1, No. 133, pp. 10-1007).

Garau, M., Slater, M., Pertaub, D., & Razzaque, S. (2005). The responses of people to virtual humans in an immersive VE. *Presence: Teleoperators & VEs*, *14*(1), 104-116.

Geller, T. (2008). Overcoming the uncanny valley. *IEEE computer graphics and applications*, *28*(4), 11-17.

Geng, J. (2013). Three-dimensional display technologies. *Advances in optics and photonics*, *5*(4), 456-535.

Gentile, D., Anderson, C., Yukawa, S., Ihori, N., Saleem, M., Ming, L., ... & Rowell Huesmann, L. (2009). The effects of prosocial video games on prosocial behaviors: International evidence from correlational, longitudinal, and experimental studies. *Personality and Social Psychology Bulletin*, *35*(6), 752-763.

Gershon, J., Zimand, E., Pickering, M., Rothbaum, B., & Hodges, L. (2004). A pilot and feasibility study of virtual reality as a distraction for children with cancer. *Journal of the American Academy of Child & Adolescent Psychiatry*, *43*(10), 1243-1249.

Gilbert, B. (2018, October 1). *'Minecraft' is still one of the biggest games in the world, with over 91 million people playing monthly*. Retrieved from https://www.businessinsider.com/minecraft-has-74-million-monthly-players-2018-1

Glicksohn, J., & Avnon, M. (1997). Explorations in virtual reality: absorption, cognition and altered state of consciousness. Imagination, Cognition and Personality, 17(2), 141–151.

Global Business Travel Association. (2018). The cost of business travel. Retrieved from https://www.gbta.org/news-and-advocacy/commentary/postid/3388/the-cost-of-business-travel

Global Business Travel Association. (2018a). Global Business Travel Spend Topped Record-Breaking $1.2 Trillion USD in 2015, Will Reach $1.6 Trillion by 2020. Retrieved from https://www.gbta.org/news-and-advocacy/newsroom/global-business-travel-spend-topped-record-breaking-12-trillion-usd-in-2015-will-reach-16-trillion-by-2020

Goncalves, R., Pedrozo, A., Coutinho, E., Figueira, I., & Ventura, P. (2012). Efficacy of virtual reality exposure therapy in the treatment of PTSD: a systematic review. *PloS one*, *7*(12).

Gorini, A., Capideville, C., De Leo, G., Mantovani, F., & Riva, G. (2011). The role of immersion and narrative in mediated presence: the virtual hospital experience. *Cyberpsychology, Behavior, and Social Networking*, *14*(3), 99-105.

Green, M., Brock, T., & Kaufman, G. (2004). Understanding media enjoyment: The role of transportation into narrative worlds. *Communication Theory*, *14*(4), 311-327.

Gregg, L., & Tarrier, N. (2007). Virtual reality in mental health. *Social psychiatry and psychiatric epidemiology*, *42*(5), 343-354.

Greitemeyer, T., & Osswald, S. (2010). Effects of prosocial video games on prosocial behavior. *Journal of personality and social psychology*, *98*(2), 211.

Griffiths, M., Davies, M., & Chappell, D. (2004). Online computer gaming: a comparison of adolescent and adult gamers. *Journal of adolescence*, *27*(1), 87-96.

Griffiths, M., Kuss, J., & King, L. (2012). Video game addiction: Past, present and future. *Current Psychiatry Reviews*, *8*(4), 308-318.

Gumbel, A. (2011, September 17). US killers blame 'The Matrix' for shootings. Retrieved from https://www.independent.co.uk/news/world/americas/us-killers-blame-the-matrix-for-shootings-5353119.html.

Gutierrez-Maldonado, J., Ferrer-Garcia, M., Caqueo-Urizar, A., & Letosa-Porta, A. (2006). Assessment of emotional reactivity produced by exposure to VEs in patients with eating disorders. *CyberPsychology & Behavior*, *9*(5), 507-513.

Gyselinck, V., De Beni, R., Pazzaglia, F., Meneghetti, C., & Mondoloni, A. (2007). Working memory components and imagery instructions in the elaboration of a spatial mental model. *Psychological Research*, *71*(3), 373.

Haans, A., & IJsselsteijn, W. (2006). Mediated social touch: a review of current research and future directions. *Virtual Reality*, *9*(2-3), 149-159.

Haans, A., & Ijsselsteijn, W. A. (2012). Embodiment and telepresence: Toward a comprehensive theoretical framework. *Interacting with Computers*, *24*(4), 211-218.

Haridy, R. (2017, March 30). Art in the age of ones and zeros: Minecraft Art. Retrieved from https://newatlas.com/art-ones-and-zeros-minecraft/48658/

Heath, A. (2017, June 20). *Facebook is still fighting a $500 million lawsuit over the fate of its virtual reality business*. Retrieved from https://www.businessinsider.com/facebook-still-fighting-oculus-vr-lawsuit-zenimax-2017-6

Hecht, D., & Reiner, M. (2006). Field dependency and the sense of object-presence in haptic VEs. *CyberPsychology & Behavior*, *10*(2), 243-251.

Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators & VEs*, *1*(2), 262-271.

Heilig, M. (1962). *U.S. Patent No. 3,050,870*. Washington, DC: U.S. Patent and Trademark Office.

Heilig, M. (1992). El cine del futuro: The cinema of the future. *Presence: Teleoperators & VEs*, *1*(3), 279-294.

Heilig, M. (1998). Beginnings: sensorama and the telesphere mask. In *Digital illusion: entertaining the future with high technology* (pp. 343-351).

Held, R., & Durlach, N. (1991). Telepresence, time delay and adaptation. *Pictorial communication in virtual and real environments*, 232-246.

Henderson, A., Korner-Bitensky, N., & Levin, M. (2007). Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. *Topics in stroke rehabilitation*, *14*(2), 52-61.

Hendrix, C., & Barfield, W. (1995, March). Presence in VEs as a function of visual and auditory cues. In *vrais* (p. 74). IEEE.

Herrera, G., Jordan, R., & Vera, L. (2006). Agency and presence: A common dependence on subjectivity?. *Presence: Teleoperators and Virtual Environments*, *15*(5), 539-552.

Herzfeld, O. (2012, December 4). *What Is the Legal Status of Virtual Goods?* Retrieved from https://www.forbes.com/sites/oliverherzfeld/2012/12/04/what-is-the-legal-status-of-virtual-goods/#35751c88108a

Hettinger, L., Nolan, M., Kennedy, R., Berbaum, K., Schnitzius, K., & Edinger, K. (1987, September). Visual display factors contributing to simulator sickness. In *Proceedings of the Human Factors Society Annual Meeting* (Vol. 31, No. 5, pp. 497-501). Sage CA: Los Angeles, CA: SAGE Publications.

Hill, R., Gratch, J., Marsella, S., Rickel, J., Swartout, W., & Traum, D. (2003). Virtual Humans in the Mission Rehearsal Exercise System. *Ki*, *17*(4), 5.

Hodges, L., Kooper, R., Meyer, T., De Graaff, J., Rothbaum, B., Opdyke, D., ... & North, M. (1994). *Presence as the defining factor in a VR application*. Georgia Institute of Technology.

Hofer, M., Hartmann, T., Eden, A., Ratan, R., & Hahn, L. (2020). The role of plausibility in the experience of spatial presence in virtual environments. *Frontiers in Virtual Reality*, *1*, 2.

Hoffman, H., Hollander, A., Schroder, K., Rousseau, S., & Furness, T. (1998). Physically touching and tasting virtual objects enhances the realism of virtual experiences. *Virtual Reality*, *3*(4), 226-234.

Hoffman, H., Patterson, D., & Carrougher, G. (2000). Use of virtual reality for adjunctive treatment of adult burn pain during physical therapy: a controlled study. *The Clinical journal of pain*, *16*(3), 244-250.

Holmes Report. (2011, April 29). The cost of poor communications. Retrieved from https://www.holmesreport.com/latest/article/the-cost-of-poor-communications

Howarth, P. (1999). Oculomotor changes within VEs. *Applied Ergonomics*, *30*(1), 59-67.

Howarth, P., & Costello, P. (1997). The occurrence of virtual simulation sickness symptoms when an HMD was used as a personal viewing system. *Displays*, *18*(2), 107-116.

Howarth, P., & Finch, M. (1999). The nauseogenicity of two methods of navigating within a VE. *Applied Ergonomics*, *30*(1), 39-45.

HTC Corporation. (2016). *Vive pre-user guide.*

Huang, M., & Alessi, N. (1999). Mental health implications for presence. *CyberPsychology & Behavior*, *2*(1), 15-18.

Huang, M., & Alessi, N. (1999a). Presence as an emotional experience. *Studies in health technology and informatics*, 148-153.

Hvass, J., Larsen, O., Vendelbo, K., Nilsson, N., Nordahl, R., & Serafin, S. (2017, June). Visual realism and presence in a virtual reality game. In *2017 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video* (pp. 1-4). IEEE.

Iachini, T., Maffei, L., Masullo, M., Senese, V. P., Rapuano, M., Pascale, A., ... & Ruggiero, G. (2019). The experience of virtual reality: are individual differences in mental imagery associated with sense of presence?. *Cognitive processing*, *20*(3), 291-298.

Ichimura, A., Nakajima, I., & Juzoji, H. (2001). Investigation and analysis of a reported incident resulting in an actual airline hijacking due to a fanatical and engrossed VR state. *CyberPsychology & Behavior*, *4*(3), 355-363.

Ijsselsteijn, W. (2002). Elements of a multi-level theory of presence: Phenomenology, mental processing and neural correlates. *Proceedings of PRESENCE*, *2002*, 245-259.

IJsselsteijn, W. (2005). History of telepresence. In *3D videocommunication: algorithms, concepts and real-time systems in human centred communication* (pp. 7-21). Wiley.

IJsselsteijn, W., Bouwhuis, D., Freeman, J., & de Ridder, H. (2002, May). P-15: Presence as an Experiential Metric for 3-D Display Evaluation. In *SID Symposium Digest of Technical Papers* (Vol. 33, No. 1, pp. 252-255). Oxford, UK: Blackwell Publishing Ltd.

IJsselsteijn, W., de Ridder, H., Freeman, J., & Avons, S. (2000, June). Presence: concept, determinants, and measurement. In *Human Vision and Electronic Imaging V* (Vol. 3959, pp. 520-530). International Society for Optics and Photonics.

IJsselsteijn, W., de Ridder, H., Freeman, J., Avons, S., & Bouwhuis, D. (2001). Effects of stereoscopic presentation, image motion, and screen size on subjective and objective corroborative measures of presence. *Presence: Teleoperators & VEs*, *10*(3), 298-311.

IJsselsteijn, W., de Ridder, H., Hamberg, R., Bouwhuis, D., & Freeman, J. (1998). Perceived depth and the feeling of presence in 3DTV. *Displays*, *18*(4), 207-214.

IJsselsteijn, W., Freeman, J., & de Ridder, H. (2001). Presence: where are we?. *Cyberpsychology, Behavior, and Social Networking*, *4*, 179-182.

Ijsselsteijn, W., Harper, B., & TPRW Group. (2001). Virtually there? A vision on presence research. *PRESENCE-IST*, *31014*, 1-27.

IJsselsteijn, W., Seuntiens, P., & Meesters, L. (2005). Human factors of 3D displays. *Schreer, Kauff, Sikora, edts.) 3D Video Communication, Wiley*.

Insko, B. (2003). Measuring presence: Subjective, behavioral and physiological methods. In *Being There: Concepts, effects and measurement of user presence in synthetic environments*.

International Society for Presence Research. (2000). *The Concept of Presence: Explication Statement.* Retrieved from https://ispr.info/

Iwata, H. (1999, March). Walking about VEs on an infinite floor. In *Virtual Reality, 1999. Proceedings., IEEE* (pp. 286-293). IEEE.

Jackson, R., Willey, C., & Cormack, L. (2013). Learning and exposure affect environmental perception less than evolutionary navigation costs. *PloS one*, *8*(4), e59690.

James, W. (1890). *The principles of psychology* (Vol. 1). Read Books Ltd.

Jancke, L., Cheetham, M., & Baumgartner, T. (2009). Virtual reality and the role of the prefrontal cortex in adults and children. *Frontiers in neuroscience*, *3*, 6.

Jelfs, A., & Whitelock, D. (2000). The notion of presence in virtual learning environments: what makes the environment "real". *British Journal of Educational Technology, 31*(2), 145-152.

Jensen, C., Pair, J., & Flores, J. (2000). The NAVE Design and Implementation of a Non-Expensive Immersive Virtual Environment 249.

Jerome, L., & Jordan, P. (2007). Psychophysiological perspective on presence: The implications of mediated environments on relationships, behavioral health and social construction. *Psychological Services*, *4*(2), 75.

Johns, C., Nunez, D., Daya, M., Sellars, D., Casanueva, J., & Blake, E. (2000). The interaction between individuals' immersive tendencies and the sensation of presence in a VE. In *VEs 2000* (pp. 65-74). Springer, Vienna.

Johnsen, E., & Corliss, W. (1971). *Human factors applications in teleoperator design and operation* (pp. 169-171). New York: Wiley-Interscience.

Kallman, E. A. (1993). Ethical evaluation: A necessary element in virtual environment research. *Presence: Teleoperators & Virtual Environments*, *2*(2), 143-146.

Kalyvioti, K., & Mikropoulos, T. (2014). Virtual environments and dyslexia: A literature review. *Procedia Computer Science*, *27*, 138-147.

Kaul, O. B., Meier, K., & Rohs, M. (2017, September). Increasing presence in virtual reality with a vibrotactile grid around the head. In *IFIP Conference on Human-Computer Interaction* (pp. 289-298). Springer, Cham.

Kennedy, R., & Frank, L. (1985). A review of motion sickness with special reference to simulator sickness. Canyon Research Group Inc. Westlake Village, California, USA.

Kennedy, R., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, *3*(3), 203-220.

King, D., Delfabbro, P., & Griffiths, M. (2010). Video game structural characteristics: A new psychological taxonomy. *International journal of mental health and addiction*, *8*(1), 90-106.

Kingdon, K., Stanney, K., & Kennedy, R. (2001, October). Extreme responses to VE exposure. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 45, No. 27, pp. 1906-1910). Sage CA: Los Angeles, CA: SAGE Publications.

Kircherr, J., & Biswas, A. (2018, September 24). Expensive academic conferences give us old ideas and no new faces. Retrieved from https://www.theguardian.com/higher-education-network/2017/aug/30/expensive-academic-conferences-give-us-old-ideas-and-no-new-faces

Kizony, R., Raz, L., Katz, N., Weingarden, H., & Weiss, P. (2005). Video-capture virtual reality system for patients with paraplegic spinal cord injury. *Journal of Rehabilitation Research & Development*, *42*(5).

Klimmt, C., & Vorderer, P. (2003). Media psychology “is not yet there”: Introducing theories on media entertainment to the presence debate. *Presence: Teleoperators & VEs*, *12*(4), 346-359.

Kline, P., & Witmer, B. (1996, October). Distance perception in VEs: Effects of field of viewfield-of-view and surface texture at near distances. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 40, No. 22, pp. 1112-1116). Sage CA: Los Angeles, CA: SAGE Publications.

Knerr, B., Lampton, D., Singer, M., Witmer, B., & Goldberg, S. (1998). *VEs for Dismounted Soldier Training and Performance: Results, Recommendations, and Issues* (No. ARI-TR-1089). Army Research Institute Field Unit Orlando FL.

Kober, S., & Neuper, C. (2012). Using auditory event-related EEG potentials to assess presence in virtual reality. *International Journal of Human-Computer Studies*, *70*(9), 577-587.

Kober, S., & Neuper, C. (2013). Personality and presence in virtual reality: does their relationship depend on the used presence measure? *International Journal of Human-Computer Interaction*, *29*(1), 13-25.

Kolasinski, E. (1995). *Simulator sickness in virtual environments* (Vol. 1027). US Army Research Institute for the Behavioral and Social Sciences.

Krassmann, A. L., Melo, M., Peixoto, B., Pinto, D., Bessa, M., & Bercht, M. (2020, July). Learning in virtual reality: Investigating the effects of immersive tendencies and sense of presence. In *International Conference on Human-Computer Interaction* (pp. 270-286). Springer, Cham.

Ku, J., Cho, W., Kim, J., Peled, A., Wiederhold, B., Wiederhold, M., ... & Kim, S. (2003). A VE for investigating schizophrenic patients' characteristics: assessment of cognitive and navigation ability. *CyberPsychology & Behavior*, *6*(4), 397-404.

Kuss, J., Griffiths, D., Karila, L., & Billieux, J. (2014). Internet addiction: A systematic review of epidemiological research for the last decade. *Current pharmaceutical design*, *20*(25), 4026-4052.

Kuzmicova, A. (2012). Presence in the reading of literary narrative: A case for motor enactment. *Semiotica*, *189*(1-4), 23-48.

Laarni, J., Ravaja, N., Saari, T., & Hartmann, T. (2004). Personality-related differences in subjective presence. In *Proceedings of the seventh annual international workshop presence* (pp. 88-95).

Lachlan, K., & Krcmar, M. (2011). Experiencing presence in video games: The role of presence tendencies, game experience, gender, and time spent in play. *Communication Research Reports*, *28*(1), 27-31.

Lambooij, M., IJsselsteijn, W., & Heynderickx, I. (2007, March). Visual discomfort in stereoscopic displays: a review. In *Stereoscopic Displays and Virtual Reality Systems XIV* (Vol. 6490, p. 64900I). International Society for Optics and Photonics.

Lampton, D., McDonald, D., Singer, M., & Bliss, J. (1995, October). Distance estimation in VEs. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 39, No. 20, pp. 1268-1272). Sage CA: Los Angeles, CA: SAGE Publications.

Lastowka, G. (2012, February 2). Dutch Supreme Court decides virtual theft case. Retrieved from http://madisonian.net/2012/02/01/dutch-supreme-court-decides-virtual-theft-case/

Lastowka, G., & Hunter, D. (2004). The laws of the virtual worlds. *Cal. L. Rev.*, *92*, 1.

Lauria, R. (1997). Virtual reality: An empirical-metaphysical testbed. *Journal of computer-mediated communication*, *3*(2), JCMC323.

Lee, J., Ku, J., Cho, W., Hahn, W., Kim, I., Lee, S., ... & Wiederhold, M. (2003). A virtual reality system for the assessment and rehabilitation of the activities of daily living. *CyberPsychology & Behavior*, *6*(4), 383-388.

Lee, J., Lim, Y., Graham, S., Kim, G., Wiederhold, B., Wiederhold, M. D., ... & Kim, S. (2004). Nicotine craving and cue exposure therapy by using virtual environments. *CyberPsychology & Behavior*, *7*(6), 705-713.

Lee, K. (2004). Why presence occurs: Evolutionary psychology, media equation, and presence. *Presence: Teleoperators & Virtual Environments*, *13*(4), 494-505.

Lee, K. (2004a). Presence, explicated. *Communication theory*, *14*(1), 27-50.

Lemley, M., & Volokh, E. (2018). Law, virtual reality, and augmented reality. *U. Pa. L. Rev.*, *166*, 1051.

Li, A., Montano, Z., Chen, V. & Gold, J. (2011). Virtual reality and pain management: current trends and future directions. *Pain management*, *1*(2), 147-157.

Liao, T., Jennings, N., Dell, L., & Collins, C. (2019). Could the virtual dinosaur see you? Understanding children's perceptions of presence and reality distinction in virtual reality environments. *Journal For Virtual Worlds Research*, *12*(2).

Lin, J., Duh, H., Parker, D., Abi-Rached, H., & Furness, T. (2002). Effects of field of viewfield-of-view on presence, enjoyment, memory, and simulator sickness in a VE. In *Virtual Reality, 2002. Proceedings. IEEE* (pp. 164-171). IEEE.

Linden Lab. (2013, June 20). Retrieved from https://www.lindenlab.com/releases/infographic-10-years-of-second-life

Ling, Y., Brinkman, W., Nefs, H., Qu, C., & Heynderickx, I. (2012). Effects of stereoscopic viewing on presence, anxiety, and cybersickness in a virtual reality environment for public speaking. *Presence: Teleoperators and Virtual Environments*, *21*(3), 254-267.

Ling, Y., Nefs, H., Morina, N., Heynderickx, I., & Brinkman, W. (2014). A meta-analysis on the relationship between self-reported presence and anxiety in virtual reality exposure therapy for anxiety disorders. *PloS one*, *9*(5), e96144.

Link, E., & Kail, K. (1944). *U.S. Patent No. 2,358,016*. Washington, DC: U.S. Patent and Trademark Office.

Lombard, M., & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication*, *3*(2).

Lombard, M., & Jones, M. (2015). Defining presence. In *Immersed in Media* (pp. 13-34). Springer, Cham.

Lombard, M., Ditton, T., Crane, D., Davis, B., Gil-Egui, G., Horvath, K., ... & Park, S. (2000, March). Measuring presence: A literature-based approach to the development of a standardized paper-and-pencil instrument. In *Third international workshop on presence, delft, the Netherlands* (Vol. 240, pp. 2-4).

Loomis, J. (1992). Distal attribution and presence. *Presence: Teleoperators & Virtual Environments*, *1*(1), 113-119.

Loren, M. (2012, August 1). *Virtual reality used to train Soldiers in new training simulator.* Retrieved from www.army.mil/article/84453/virtual_reality_used_to_train_soldiers_in_new_training_simulator

Malloy, K., & Milling, L. (2010). The effectiveness of virtual reality distraction for pain reduction: a systematic review. *Clinical psychology review*, *30*(8), 1011-1018.

Mantovani, G., & Riva, G. (1999). “Real” presence: how different ontologies generate different criteria for presence, telepresence, and virtual presence. *Presence*, *8*(5), 540-550.

Marshall, P. (2016). Virtual reality: Will consumers embrace the emerging technology? *CQ Researcher.* SAGE Publications.

Mason, A., Walji, M., Lee, E., & MacKenzie, C. (2001, March). Reaching movements to augmented and graphic objects in VEs. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 426-433). ACM.

Mazuryk, T., & Gervautz, M. (1996). Virtual reality-history, applications, technology and future.

McCloy, R., & Stone, R. (2001). Virtual reality in surgery. *Bmj*, *323*(7318), 912-915.

McCreary, F., & Williges, R. (1998, October). Effects of age and field-of-view on spatial learning in an immersive VE. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 42, No. 21, pp. 1491-1495). Sage CA: Los Angeles, CA: SAGE Publications.

McCreery, M., Schrader, P., Krach, S., & Boone, R. (2013). A sense of self: The role of presence in virtual environments. *Computers in Human Behavior*, *29*(4), 1635-1640.

McIntosh, J. (2017, June 14). How It Works: Ford's virtual reality design studios. Retrieved from https://driving.ca/ford/auto-news/news/how-it-works-ford-design-studios

Meehan, M., Insko, B., Whitton, M., & Brooks, F. (2002). Physiological measures of presence in stressful VEs. *ACM transactions on graphics (tog)*, *21*(3), 645-652.

Meehan, M., Razzaque, S., Whitton, M., & Brooks, F. (2003, March). Effect of latency on presence in stressful VEs. In *null* (p. 141). IEEE.

Meesters, L., IJsselsteijn, W., & Seuntieens, P. (2004). A survey of perceptual evaluations and requirements of three-dimensional TV. *IEEE Transactions on circuits and systems for video technology*, *14*(3), 381-391.

Mehrabian, A., & Ferris, S. (1967). Inference of attitudes from nonverbal communication in two channels. *Journal of consulting psychology*, *31*(3), 248.

Meola, A. (2017, July 13). Drone market shows positive outlook with strong industry growth and trends. Retrieved from https://www.businessinsider.com/drone-industry-analysis-market-trends-growth-forecasts-2017-7

Mikkola, M., Boev, A., & Gotchev, A. (2010, October). Relative importance of depth cues on portable autostereoscopic display. In *Proceedings of the 3rd workshop on Mobile video delivery* (pp. 63-68). ACM.

Mikropoulos, T., & Strouboulis, V. (2004). Factors that influence presence in educational VEs. *CyberPsychology & Behavior, 7*(5), 582-591.

Miller, J. (2017, November 28). *Vet accused of sending reporter seizure-causing tweet catches small break*. Retrieved from https://nypost.com/2017/11/28/vet-accused-of-sending-reporter-seizure-causing-tweet-catches-small-break/

Miller, J., Sharkey, T., Graham, G., & McCauley, M. (1993). Autonomic physiological data associated with simulator discomfort. *Aviation, space, and environmental medicine*, *64*(9 Pt 1), 813-819.

Mine, M. (1993). Characterization of end-to-end delays in head-mounted display systems. *The University of North Carolina at Chapel Hill, TR93-001*.

Minsky, M. (1980). Telepresence. *Omni*, pp. 45–51.

Mitchell, W., Szerszen, K., Lu, A., Schermerhorn, P., Scheutz, M., & MacDorman, K. (2011). A mismatch in the human realism of face and voice produces an uncanny valley. *i-Perception*, *2*(1), 10-12.

Mori, M. (1970). The uncanny valley. *Energy*, *7*(4), 33-35.

Mraz, R., Hong, J., Quintin, G., Staines, W., McIlroy, W., Zakzanis, K., & Graham, S. (2003). A platform for combining virtual reality experiments with functional magnetic resonance imaging. *CyberPsychology & Behavior*, *6*(4), 359-368.

Muijen, G. (2015). Property rights in virtual objects: How a qualified normative approach to virtual property rights can benefit users and developers of MMOGs.

Mujber, T., Szecsi, T., & Hashmi, M. (2004). Virtual reality applications in manufacturing process simulation. *Journal of materials processing technology*, *155*, 1834-1838.

Munafo, J., Diedrick, M., & Stoffregen, T. (2017). The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Experimental brain research*, *235*(3), 889-901.

Munyan, B., Neer, S., Beidel, D., & Jentsch, F. (2016). Olfactory stimuli increase presence in virtual environments. *PloS one*, *11*(6), e0157568.

Murray, C., Fox, J., & Pettifer, S. (2007). Absorption, dissociation, locus of control and presence in virtual reality. *Computers in Human Behavior*, *23*(3), 1347-1354.

Myers, I. (1962). The Myers-Briggs Type Indicator: Manual (1962).

National Security Agency. (2011). Virtual reality. Cyrptologic Quarterly (Document ID: 3929132).

Nawrot, M. (2003). Depth from motion parallax scales with eye movement gain. *Journal of Vision*, *3*(11), 17-17.

Neale, D. (1997, October). Factors influencing spatial awareness and orientation in desktop VEs. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 41, No. 2, pp. 1278-1282). Sage CA: Los Angeles, CA: SAGE Publications.

Neilsen Group: Super Data. (2020). *2019 Year in review*. Retrieved from https://direc.ircg.ir/wp-content/uploads/2020/01/SuperData2019YearinReview.pdf

New York Times. (2008, October 24). *Woman arrested for 'killing' her virtual husband*. Retrieved from https://www.nytimes.com/2008/10/24/world/asia/24iht-virtual.1.17223730.html

Newbutt, N. (2010, March). A brief review: assistive technology and autism, a proposal for virtual tools for improved communication and emotional recognition. In *Society for Information Technology & Teacher Education International Conference* (pp. 1998-2003). Association for the Advancement of Computing in Education (AACE).

Nichols, S. (1999). Physical ergonomics of VE use. *Applied Ergonomics*, *30*(1), 79-90.

Nichols, S., Cobb, S., & Wilson, J. (1997). Health and safety implications of VEs: Measurement issues. *Presence: Teleoperators & VEs*, *6*(6), 667-675.

Nichols, S., Haldane, C., & Wilson, J. (1999). Measurement of presence and its consequences in virtual environments. *International Journal of Human-Computer Studies*, *52*(3), 471-491.

Norman, K. (2018). Evaluation of Virtual Reality Games: Simulator Sickness and Human Factors. In *GHItaly@ AVI*.

Norouzi, N., Bruder, G., & Welch, G. (2018, August). Assessing vignetting as a means to reduce VR sickness during amplified head rotations. In *Proceedings of the 15th ACM Symposium on Applied Perception* (pp. 1-8).

North, M., & North, S. (2018). The sense of presence exploration in virtual reality therapy. *J. UCS*, *24*(2), 72-84.

Nowak, K., & Biocca, F. (2003). The effect of the agency and anthropomorphism on users' sense of telepresence, copresence, and social presence in VEs. *Presence: Teleoperators & VEs*, *12*(5), 481-494.

Nowak, K., Krcmar, M., & Farrar, K. (2008). The causes and consequences of presence: Considering the influence of violent video games on presence and aggression. *Presence: Teleoperators and VEs*, *17*(3), 256-268.

Nystad, E., & Sebok, A. (2004, October). A comparison of two presence measures based on experimental results. In *Proceedings of the seventh international workshop on presence* (pp. 266-273).

Obrist, M., Velasco, C., Vi, C., Ranasinghe, N., Israr, A., Cheok, A., ... & Gopalakrishnakone, P. (2016). Sensing the future of HCI: touch, taste, and smell user interfaces. *interactions*, *23*(5), 40-49.

Oing, T., & Prescott, J. (2018). Implementations of virtual reality for anxiety-related disorders: systematic review. *JMIR serious games*, *6*(4), e10965.

Parise, S., Kiesler, S., Sproull, L., & Waters, K. (1996, November). My partner is a real dog: Cooperation with social agents. In *Proceedings of the 1996 ACM conference on Computer supported cooperative work* (pp. 399-408). ACM.

Parola, M., Johnson, S., & West, R. (2016). Turning presence inside-out: Metanarratives. *Electronic Imaging*, *2016*(4), 1-9.

Park, S., & Catrambone, R. (2007). Social facilitation effects of virtual humans. *Human factors*, *49*(6), 1054-1060.

Parsons, T., & Rizzo, A. (2008). Affective outcomes of virtual reality exposure therapy for anxiety and specific phobias: A meta-analysis. *Journal of behavior therapy and experimental psychiatry*, *39*(3), 250-261.

Parsons, T., Rizzo, A., Rogers, S., & York, P. (2009). Virtual reality in paediatric rehabilitation: a review. *Developmental neurorehabilitation*, *12*(4), 224-238.

Paton, C. (2017, December 23). A virtual reality gamer has died from blood loss after slipping. Retrieved from https://www.newsweek.com/virtual-reality-gamer-slips-and-dies-blood-loss-after-falling-glass-table-757966

Pausch, R., Snoddy, J., Taylor, R., Watson, S., & Haseltine, E. (1996, August). Disney's Aladdin: first steps toward storytelling in virtual reality. In *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques* (pp. 193-203). ACM.

Pepitone, J. (2016, October 25). Designing the workplace of the future: Virtual reality and 3D panoramas. Retrieved from https://money.cnn.com/gallery/technology/2016/10/25/workplace-of-the-future/index.html

Perry, S., Heidrich, G., & Ramos, E. (1981). Assessment of pain by burn patients. *The Journal of burn care & rehabilitation*, *2*(6), 322-326.

Petkova, V., & Ehrsson, H. (2008). If I were you: perceptual illusion of body swapping. *PloS one*, *3*(12), e3832.

Pinkwart, N., & Olivier, H. (2009). Cooperative virtual worlds—a viable eCollaboration pathway or merely a gaming trend?. *Electronic Markets*, *19*(4), 233.

Pittaro, M. (2007). Cyber stalking: An analysis of online harassment and intimidation. *International Journal of Cyber Criminology*, *1*(2), 180-197.

Plato. *The Republic*. The Academy, Athens, c.375 BC.

Poeschl, S., Wall, K., & Doering, N. (2013, March). Integration of spatial sound in immersive virtual environments an experimental study on effects of spatial sound on presence. In *2013 IEEE Virtual Reality (VR)* (pp. 129-130). IEEE.

Poupyrev, I., Billinghurst, M., Weghorst, S., & Ichikawa, T. (1996, November). The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th annual ACM symposium on User interface software and technology* (pp. 79-80).

Poupyrev, I., Weghorst, S., Billinghurst, M., & Ichikawa, T. (1997, September). A framework and testbed for studying manipulation techniques for immersive VR. In *Proceedings of the ACM symposium on Virtual reality software and technology* (pp. 21-28).

Prothero, J., Hoffman, H., Parker, D., Furness III, T., & Wells, M. (1995, October). Foreground/background manipulations affect presence. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 39, No. 21, pp. 1410-1414). Sage CA: Los Angeles, CA: SAGE Publications.

Raja, D., Bowman, D., Lucas, J., & North, C. (2004, May). Exploring the benefits of immersion in abstract information visualization. In *Proc. Immersive Projection Technology Workshop* (pp. 61-69).

Ramachandran, V., & Anstis, S. (1986). The perception of apparent motion. *Scientific American*, *254*(6), 102-109.

Ratan, R., Santa Cruz, M., & Vorderer, P. (2007). Multitasking, presence, and self-presence on the Wii. In *Proceedings of the 10th Annual International Workshop on Presence* (pp. 167-190). Starlab Barcelona SL.

Razzaque, S., Swapp, D., Slater, M., Whitton, M., & Steed, A. (2002, May). Redirected walking in place. In *EGVE* (Vol. 2, pp. 123-130).

Reiner, M. (2004). The role of haptics in immersive telecommunication environments. *IEEE Transactions on Circuits and Systems for Video Technology*, *14*(3), 392-401.

Rey, B., Alcaniz, M., Tembl, J., & Parkhutik, V. (2008). Brain activity and presence: a preliminary study in different immersive conditions using transcranial Doppler monitoring. *Virtual Reality*, *14*(1), 55-65.

Richardson, A., & Waller, D. (2007). Interaction with an immersive VE corrects users' distance estimates. *Human Factors*, *49*(3), 507-517.

Rickenberg, R., & Reeves, B. (2000, April). The effects of animated characters on anxiety, task performance, and evaluations of user interfaces. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (pp. 49-56). ACM.

Riva, G., & Waterworth, J. (2003). Presence and the Self: A cognitive neuroscience approach. *Presence connect*, *3*(3).

Riva, G., Waterworth, J., & Waterworth, E. (2004). The layers of presence: a bio-cultural approach to understanding presence in natural and mediated environments. *CyberPsychology & Behavior*, *7*(4), 402-416.

Roberts, J. (2017, April 25). *Journalist Sues Troll Over Twitter Epilepsy Assault*. Retrieved from http://fortune.com/2017/04/25/eichenwald-tweet-twitter-troll/

Robinett, W. (1992). Synthetic experience: A proposed taxonomy. *Presence: Teleoperators & VEs*, *1*(2), 229-247.

Rogers, S. (2019, January 30). The arrival of 5G will unlock the full potential of VR and AR. Retrieved from https://www.forbes.com/sites/solrogers/2019/01/30/the-arrival-of-5g-will-unlock-the-full-potential-of-vr-and-ar/#53b874367bcc

Rosenberg, R., Baughman, S., & Bailenson, J. (2013). Virtual superheroes: Using superpowers in virtual reality to encourage prosocial behavior. *PloS one*, *8*(1), e55003.

Rosenbloom, N. (2004). From Regulation to Censorship: Film and Political Culture in New York in the Early Twentieth Century. *The Journal of the Gilded Age and Progressive Era*, *3*(4), 369-406.

Rothbaum, B., Hodges, L., Anderson, P., Price, L., & Smith, S. (2002). Twelve-month follow-up of virtual reality and standard exposure therapies for the fear of flying. *Journal of consulting and clinical psychology*, *70*(2), 428.

Rotter, J. (1966). Generalized expectancies for internal versus external control of reinforcement. *Psychological monographs: General and applied*, *80*(1), 1.

Roussos, M., Johnson, A., Leigh, J., Vasilakis, C., Barnes, C., & Moher, T. (1997). NICE: combining constructionism, narrative and collaboration in a virtual learning environment. *Computer Graphics New York Association for Computing*, *31*, 62-63.

Rushton, S., & Riddell, P. (1999). Developing visual systems and exposure to virtual reality and stereo displays: some concerns and speculations about the demands on accommodation and vergence. *Applied Ergonomics*, *30*(1), 69-78.

Rushton, S., Mon-Williams, M., & Wann, J. (1994). Binocular vision in a bi-ocular world: new-generation head-mounted displays avoid causing visual deficit. *Displays*, *15*(4), 255-260.

Sacau, A., Laarni, J., Ravaja, N., & Hartmann, T. (2005). The impact of personality factors on the experience of spatial presence. In *The 8th International Workshop on Presence (Presence 2005)* (pp. 143-151).

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), 1005-1017.

Sadowski, W., & Stanney, K. (2002). Presence in virtual environments.

Salisbury, J., & Srinivasan, M. (1997). Phantom-based haptic interaction with virtual objects. *IEEE Computer Graphics and Applications*, *17*(5), 6-10.

Sallnas, E. (1999, April). Presence in multimodal interfaces. In *2nd International Workshop on Presence, University of Essex, Colchester* (pp. 6-7).

Sanchez-Vives, M., & Slater, M. (2005). From presence to consciousness through virtual reality. *Nature Reviews Neuroscience*, *6*(4), 332-339.

Sas, C. (2004, June). Individual differences in VEs. In *International Conference on Computational Science* (pp. 1017-1024). Springer, Berlin, Heidelberg.

Sas, C., & O'Hare, G. (2003). Presence equation: An investigation into cognitive factors underlying presence. *Presence: Teleoperators & VEs*, *12*(5), 523-537.

Sas, C., & O'Hare, G. (2003a). Impact of cognitive style upon sense of presence. In *Proceedings of HCI International* (pp. 696-700).

Sas, C., O'Hare, G., & Reilly, R. (2004). Presence and task performance: an approach in the light of cognitive style. *Cognition, Technology & Work*, *6*(1), 53-56.

Schiano, D. (1997). Convergent methodologies in cyber-psychology: A case study. *Behavior Research Methods, Instruments, & Computers*, *29*(2), 270-273.

Schloerb, D. (1995). A quantitative measure of telepresence. *Presence: Teleoperators & VEs*, *4*(1), 64-80.

Schlogl, A., Slater, M., & Pfurtscheller, G. (2002, October). Presence research and EEG. In *Proceedings of the 5th International Workshop on Presence* (Vol. 1, pp. 9-11).

Schroeder, R. (Ed.). (2002). *The social life of avatars: Presence and interaction in shared VEs*. Springer Science & Business Media.

Schubert, T., & Crusius, J. (2002). Five theses on the book problem: Presence in books, film and VR. In *PRESENCE 2002-Proceedings of the fifth international workshop on Presence* (pp. 53-59). Porto, Portugal: Universidad Fernando Pessoa.

Schubert, T., Friedmann, F., & Regenbrecht, H. (1999). Embodied presence in VEs. In *Visual representations and interpretations* (pp. 269-278). Springer, London.

Schubert, T., Friedmann, F., & Regenbrecht, H. (1999a, April). Decomposing the sense of presence: Factor analytic insights. In *2nd international workshop on presence* (Vol. 1999).

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence: Teleoperators & VEs*, *10*(3), 266-281.

Schubert, T., Regenbrecht, H., & Schubert, T. (2000). Real and illusory interactions enhance presence in VEs. In *Proceedings of the 3rd International Workshop on Presence.*

Schuemie, M., Abel, B., van der Mast, C., Krijn, M., & Emmelkamp, P. (2005). The effect of locomotion technique on presence, fear and usability in a VE. In *EUROMEDIA* (Vol. 2005, p. 11th).

Schuemie, M., Van Der Straaten, P., Krijn, M., & Van Der Mast, C. (2001). Research on presence in virtual reality: A survey. *CyberPsychology & Behavior*, *4*(2), 183-201.

Schultz, S., North, S., & Shields, C. (2007). Schizophrenia: a review. *American family physician*, *75*(12), 1821-1829.

Schulzke, M. (2010). Defending the morality of violent video games. *Ethics and Information Technology*, *12*(2), 127-138.

Seth, A. K., Suzuki, K., & Critchley, H. D. (2012). An interoceptive predictive coding model of conscious presence. *Frontiers in psychology*, *2*, 395.

Seth, A., Vance, J., & Oliver, J. (2011). Virtual reality for assembly methods prototyping: a review. *Virtual reality*, *15*(1), 5-20.

Seyama, J., & Nagayama, R. S. (2007). The uncanny valley: Effect of realism on the impression of artificial human faces. *Presence: Teleoperators and VEs*, *16*(4), 337-351.

Seymour, N., Gallagher, A., Roman, S., O'Brien, M., Bansal, V., Andersen, D., & Satava, R. (2002). Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Annals of surgery*, *236*(4), 458.

Sharpe, L., Stockman, A., Jagle, H., & Nathans, J. (1999). Opsin genes, cone photopigments, color vision, and color blindness. *Color vision: From genes to perception*, 3-51.

Sharples, S., Cobb, S., Moody, A., & Wilson, J. (2007). Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays*, *29*(2), 58-69.

Sheridan, T. (1992). Defining our terms. *Presence: Teleoperators & Virtual Environments*, *1*(2), 272-274.

Sheridan, T. (1992a). Musings on telepresence and virtual presence. *Presence: Teleoperators & VEs*, *1*(1), 120-126.

Sheridan, T. (1993). My anxieties about virtual environments. *Presence: Teleoperators & Virtual Environments*, *2*(2), 141-142.

Sheridan, T. (1994). Further musings on the psychophysics of presence. *Presence: Teleoperators & VEs*, *5*(2), 241-246.

Simons, D., & Chabris, C. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *perception*, *28*(9), 1059-1074.

Siriaraya, P., & Siang Ang, C. (2012). Age differences in the perception of social presence in the use of 3D virtual world for social interactionq. *Interacting with Computers*, *24*(4), 280-291.

Skarbez, R., Brooks, Jr, F. P., & Whitton, M. C. (2017). A survey of presence and related concepts. *ACM Computing Surveys (CSUR)*, *50*(6), 1-39.

Slater, M. (1999). Measuring presence: A response to the Witmer and Singer presence questionnaire. *Presence*, *8*(5), 560-565.

Slater, M. (1999a). Real people meeting virtually real people—a review of some experiments in shared VEs. *BT Technology Journal*, *17*(1), 120-127.

Slater, M. (2003). A note on presence terminology. *Presence connect*, *3*(3), 1-5.

Slater, M. (2004). How colorful was your day? Why questionnaires cannot assess presence in VEs. *Presence: Teleoperators & VEs*, *13*(4), 484-493.

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive VEs. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *364*(1535), 3549-3557.

Slater, M., & Wilbur, S., 1997. A framework for immersive VEs (FIVE): speculations on the role of presence in VEs. Presence 6 (6), 603.

Slater, M., Brogni, A., & Steed, A. (2003, October). Physiological responses to breaks in presence: A pilot study. In *Presence 2003: The 6th Annual International Workshop on Presence* (Vol. 157). Citeseer.

Slater, M., Khanna, P., Mortensen, J., & Yu, I. (2009). Visual realism enhances realistic response in an immersive VE. *IEEE computer graphics and applications*, *29*(3).

Slater, M., Linakis, V., Usoh, M., Kooper, R., & Street, G. (1996, July). Immersion, presence, and performance in VEs: An experiment with tri-dimensional chess. In *ACM virtual reality software and technology (VRST)* (Vol. 163, p. 72). New York, NY: ACM Press.

Slater, M., Steed, A., McCarthy, J., & Maringelli, F. (1998). The influence of body movement on subjective presence in VEs. *Human Factors*, *40*(3), 469-477.

Slater, M., Usoh, M., & Chrysanthou, Y. (1995). The influence of dynamic shadows on presence in immersive VEs. In *VEs' 95* (pp. 8-21). Springer, Vienna.

Slater, M., Usoh, M., & Steed, A. (1994). Steps and ladders in virtual reality. In *Virtual Reality Software and Technology* (pp. 45-54).

Slater, M., Usoh, M., & Steed, A. (1995). Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *2*(3), 201-219.

Sony. (2011). 3D TV: BRAVIA TV: Sony Philippines. Retrieved from https://www.sony.com.ph/microsite/bravia/3d-tv.html

Spagnolli, A., & Gamberini, L. (2004). The sense of being 'There': a model for the space of presence. *EXPLORING THE SENSE OF PRESENCE*, *48*.

Spiegel, J. (2018). The ethics of virtual reality technology: social hazards and public policy recommendations. *Science and engineering ethics*, *24*(5), 1537-1550.

Srinivasan, M., & Basdogan, C. (1997). Haptics in VEs: Taxonomy, research status, and challenges. *Computers & Graphics*, *21*(4), 393-404.

Stanney, K., Hale, K., Nahmens, I., & Kennedy, R. (2003). What to expect from immersive VE exposure: Influences of gender, body mass index, and past experience. *Human Factors*, *45*(3), 504-520.

Stanney, K., Kennedy, R., Drexler, J., & Harm, D. (1999). Motion sickness and proprioceptive aftereffects following VE exposure. *Applied ergonomics*, *30*(1), 27-38.

Stanney, K., Mourant, R., & Kennedy, R. (1998). Human factors issues in VEs: A review of the literature. *Presence*, *7*(4), 327-351.

Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of communication*, *42*(4), 73-93.

Stevens, B., & Jerrams-Smith, J. (2001). The sense of object-presence with projection-augmented models. In *Haptic Human-Computer Interaction* (pp. 194-198). Springer, Berlin, Heidelberg.

Stoakley, R., Conway, M., & Pausch, R. (1995, May). Virtual reality on a WIM: interactive worlds in miniature. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 265-272). ACM Press/Addison-Wesley Publishing Co.

Stoffregen, T. A., Bardy, B. G., Smart, L. J., & Pagulayan, R. J. (2003). On the nature and evaluation of fidelity in virtual environments. *Virtual and adaptive environments: Applications, implications, and human performance issues*, 111-128.

Strauss, S. (1998). Cybersickness: the side effects of virtual reality. *Technology Review*, *98*(5), 14-16.

Sutherland, I. (1965). The ultimate display. *Multimedia: From Wagner to virtual reality*, 506-508.

Sutherland, I. (1968, December). A head-mounted three-dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I* (pp. 757-764). ACM.

Sveistrup, H., McComas, J., Thornton, M., Marshall, S., Finestone, H., McCormick, A., ... & Mayhew, A. (2003). Experimental studies of virtual reality-delivered compared to conventional exercise programs for rehabilitation. *CyberPsychology & Behavior*, *6*(3), 245-249.

Taffou, M., Chapoulie, E., David, A., Guerchouche, R., Drettakis, G., & Viaud-Delmon, I. (2012). Auditory-visual integration of emotional signals in a VE for cynophobia. *Annual Review of Cybertherapy and Telemedicine 2012*, 238.

Takemura, H., & Kishino, F. (1992, December). Cooperative work environment using virtual workspace. In *Proceedings of the 1992 ACM conference on Computer-supported cooperative work* (pp. 226-232). ACM.

Tan, D., Robertson, G., & Czerwinski, M. (2001, March). Exploring 3D navigation: combining speed-coupled flying with orbiting. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 418-425).

Tarr, M., & Warren, W. (2002). Virtual reality in behavioral neuroscience and beyond. *nature neuroscience*, *5*, 1089.

Tart, C. (1972). States of consciousness and state-specific sciences. *Science*, *176*(4040), 1203-1210.

Tart, C. (1986). Consciousness, altered states, and worlds of experience. *Journal of Transpersonal Psychology*, *18*(2), 159-170

Tellegen, A., & Atkinson, G. (1974). Openness to absorbing and self-altering experiences ("absorption"), a trait related to hypnotic susceptibility. *Journal of abnormal psychology*, *83*(3), 268.

Tichon, J., & Burgess-Limerick, R. (2011). A review of virtual reality as a medium for safety related training in mining. *Journal of Health & Safety Research & Practice*, *3*(1), 33-40.

Timmins, L., & Lombard, M. (2005). When "real" seems mediated: Inverse presence. *Presence: Teleoperators & Virtual Environments*, *14*(4), 492-500.

Towell, J., & Towell, E. (1997). Presence in text-based networked VEs or "MUDS". *Presence: Teleoperators & VEs*, *6*(5), 590-595.

Trika, S., Banerjee, P., & Kashyap, R. (1997). Virtual reality interfaces for feature-based computer-aided design systems. *Computer-Aided Design*, *29*(8), 565-574.

Turkle, S. (1994). Constructions and reconstructions of self in virtual reality: Playing in the MUDs. *Mind, Culture, and Activity*, *1*(3), 158-167.

U.S. Army. (2010). *Virtual Training Benefits Teams to Battalions*. Retrieved from https://www.army.mil/article/84453/https://www.army.mil/article/39434/virtual_training_benefits_teams_to_battalions

U.S. Army. (2019). Engagement skills trainer (EST) II. Retrieved from https://asc.army.mil/web/portfolio-item/engagement-skills-trainer-est/

U.S. Census Bureau (2017). *Household Income: 2016*. Retreived from www.census.gov/content/dam/Census/library/publications/2017/acs/acsbr16-02.pdf

U.S. Congress (1994). Office of technology assessment, virtual reality technologies for combat simulation-back-ground paper.

Usoh, M., & Slater, M. (1995). An exploration of immersive VEs. *Endeavour*, *19*(1), 34-8.

Usoh, M., Arthur, K., Whitton, M., Bastos, R., Steed, A., Slater, M., & Brooks, F. (1999, July). Walking> walking-in-place> flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques* (pp. 359-364).

Usoh, M., Catena, E., Arman, S., & Slater, M. (2000). Using presence questionnaires in reality. *Presence: Teleoperators & VEs*, *9*(5), 497-503.

Valmaggia, L., Freeman, D., Green, C., Garety, P., Swapp, D., Antley, A., ... & Slater, M. (2007). Virtual reality and paranoid ideations in people with an 'at-risk mental state' for psychosis. *The British Journal of Psychiatry*, *191*(S51), s63-s68.

Van Baren, J., & Ijsselsteijn, W. (2004). Measuring presence: a guide to current measurement approaches. *OmniPres project IST-2001-39237, Project Report*.

Van Heugten-van der Kloet, D., Cosgrave, J., van Rheede, J., & Hicks, S. (2018). Out-of-body experience in virtual reality induces acute dissociation. *Psychology of Consciousness: Theory, Research, and Practice*, *5*(4), 346.

Van Schaik, P., Turnbull, T., Wersch, A., & Drummond, S. (2004). Presence within a mixed reality environment. *CyberPsychology & Behavior*, *7*(5), 540-552.

Vastfjall, D. (2003). The subjective sense of presence, emotion recognition, and experienced emotions in auditory VEs. *CyberPsychology & Behavior*, *6*(2), 181-188.

Viaud-Delmon, I., Warusfel, O., Seguelas, A., Rio, E., & Jouvent, R. (2006). High sensitivity to multisensory conflicts in agoraphobia exhibited by virtual reality. *European Psychiatry*, *21*(7), 501-508.

Villani, D., Repetto, C., Cipresso, P., & Riva, G. (2012). May I experience more presence in doing the same thing in virtual reality than in reality? An answer from a simulated job interview. *Interacting with Computers*, *24*(4), 265-272.

Villani, D., Riva, F., & Riva, G. (2007). New technologies for relaxation: The role of presence. *International Journal of Stress Management*, *14*(3), 260.

Volbracht, S., & Domik, G. (2000). Developing effective navigation techniques in virtual 3d environments. In *VEs 2000* (pp. 55-64). Springer, Vienna.

Vora, J., Nair, S., Gramopadhye, A., Duchowski, A., Melloy, B., & Kanki, B. (2002). Using virtual reality technology for aircraft visual inspection training: presence and comparison studies. *Applied ergonomics*, *33*(6), 559-570.

Wallach, H., Safir, M., & Samana, R. (2010). Personality variables and presence. *Virtual Reality*, *14*(1), 3-13.

Waller, D., Bachmann, E., Hodgson, E., & Beall, A. (2007). The HIVE: A huge immersive VE for research in spatial cognition. *Behavior Research Methods*, *39*(4), 835-843.

Walshe, D., Lewis, E., Kim, S., O'Sullivan, K., & Wiederhold, B. (2003). Exploring the use of computer games and virtual reality in exposure therapy for fear of driving following a motor vehicle accident. *CyberPsychology & Behavior*, *6*(3), 329-334.

Wang, G. (2002). Definition and review of virtual prototyping. *J. Comput. Inf. Sci. Eng.*, *2*(3), 232-236.

Wang, Y., Otitoju, K., Liu, T., Kim, S., & Bowman, D. (2006, November). Evaluating the effects of real worldreal-world distraction on user performance in VEs. In *Proceedings of the ACM symposium on Virtual reality software and technology* (pp. 19-26). ACM.

Wann, J., & Mon-Williams, M. (1996). What does virtual reality NEED?: human factors issues in the design of three-dimensional computer environments. *International Journal of Human-Computer Studies*, *44*(6), 829-847.

Ware, C., Arthur, K., & Booth, K. (1993, May). Fish tank virtual reality. In *Proceedings of the INTERACT'93 and CHI'93 conference on Human factors in computing systems* (pp. 37-42). ACM.

Waterworth, E., & Waterworth, J. (2001). Focus, locus, and sensus: The three dimensions of virtual experience. *CyberPsychology & Behavior*, *4*(2), 203-213.

Waterworth, E., Häggkvist, M., Jalkanen, K., Olsson, S., Waterworth, J., Antonsson, E., ... & Freeman, J. (2004, July). Eyes Open or Closed: Is a virtual beach more relaxing than an imagined beach. In *Fourth International Conference on Design and Emotion, Middle East Technical University, Ankara, Turkey* (Vol. 12).

Waterworth, J., & Waterworth, E. (2003). The meaning of presence. *Presence-Connect 3*.

Waterworth, J., & Waterworth, E. (2003a). The core of presence: Presence as perceptual illusion. *Presence connect*, *3*(3).

Wells, S. (2010, November 18). *Virtual training at Fort Bragg geared toward saving Soldiers' lives*. Retrieved from https://www.army.mil/article/48336/virtual_training_at_fort_bragg_geared_toward_saving_soldiers_lives

Whalen, T., Petriu, D., Yang, L., Petriu, E., & Cordea, M. (2003). Capturing behaviour for the use of avatars in VEs. *CyberPsychology & Behavior*, *6*(5), 537-544.

Wheatstone, C. (1838). XVIII. Contributions to the physiology of vision. Part the first. on some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical transactions of the Royal Society of London*, *128*, 371-394.

Whitbeck, C. (1993). Virtual environments: Ethical issues and significant confusions. *Presence: Teleoperators & Virtual Environments*, *2*(2), 147-152.

Whitby, B. (1993). The virtual sky is not the limit: Ethics in virtual reality. *Digital Creativity (Intelligent Tutoring Media)*, *4*(1), 23-28.

Whitelock, D., Romano, D., Jelfs, A., & Brna, P. (2000). Perfect presence: What does this mean for the design of virtual learning environments?. *Education and information technologies*, *5*(4), 277-289.

Wiederhold, B., Davis, R., & Wiederhold, M. (1998). The effects of immersiveness on physiology. In G. Riva, B. K. Wiederhold, & E. Molinari (Eds.), *Studies in health technology and informatics, Vol. 58. VEs in clinical psychology and neuroscience: Methods and techniques in advanced patient–therapist interaction* (pp. 52-60). Amsterdam, Netherlands: IOS Press.

Wiederhold, B., Jang, D. P., Kaneda, M., Cabral, I., Lurie, Y., May, T., ... & Kim, S. (2001). An investigation into physiological responses in VEs: an objective measurement of presence. *Towards cyberpsychology: Mind, cognitions and society in the internet age*.

Wilson, J. R. (1996). Effects of participating in VEs: A review of current knowledge. *Safety science*, *23*(1), 39-51.

Wilson, J., & D'Cruz, M. (2006). Virtual and interactive environments for work of the future. *International Journal of Human-Computer Studies*, *64*(3), 158-169.

Winn, W. (1993). A conceptual basis for educational applications of virtual reality. *Technical Publication R-93-9, Human Interface Technology Laboratory of the Washington Technology Center, Seattle: University of Washington.*

Wirth, W., Hartmann, T., Bocking, S., Vorderer, P., Klimmt, C., Schramm, H., ... & Jancke, P. (2007). A process model of the formation of spatial presence experiences. *Media psychology*, *9*(3), 493-525.

Wirth, W., Hofer, M., & Schramm, H. (2012). The role of emotional involvement and trait absorption in the formation of spatial presence. *Media Psychology*, *15*(1), 19-43.

Wirth, W., Wolf, S., Mögerle, U., & Böcking, S. (2004). Measuring the subjective experience of presence with Think-Aloud method: Theory, instruments, implications. In *Proceedings of the Seventh Annual International Workshop on Presence* (pp. 351-358).

Witmer, B., & Singer, M. (1994). *Measuring immersion in virtual environments*. Tech. Rep. 1014, US Army Research Institute for the Behavioral and Social Sciences.

Witmer, B., & Singer, M. (1998). Measuring presence in VEs: A presence questionnaire. *Presence*, *7*(3), 225-240.

Witmer, B., Jerome, C., & Singer, M. (2005). The Factor structure of the presence questionnaire. *Presence: Teleoperators & VEs*, *14*(3), 298-312.

Woolley, D. G., Vermaercke, B., de Beeck, H. O., Wagemans, J., Gantois, I., D'Hooge, R., ... & Wenderoth, N. (2010). Sex differences in human virtual water maze performance: Novel measures reveal the relative contribution of directional responding and spatial knowledge. *Behavioural brain research*, *208*(2), 408-414.

Yee, N., & Bailenson, J. (2007). The Proteus effect: The effect of transformed self-representation on behavior. *Human communication research*, *33*(3), 271-290.

Yildirim, C. (2019). Don't make me sick: investigating the incidence of cybersickness in commercial virtual reality headsets. *Virtual Reality*, 1-9.

Youngblut, C., & Huie, O. (2003, March). The relationship between presence and performance in virtual environments: Results of a VERTS study. In *IEEE Virtual Reality, 2003. Proceedings.* (pp. 277-278). IEEE.

Zahorik, P., & Jenison, R. (1998). Presence as being-in-the-world. *Presence*, *7*(1), 78-89.

Zanbaka, C., Babu, S., Xiao, D., Ulinski, A., Hodges, L. F., & Lok, B. (2004, March). Effects of travel technique on cognition in virtual environments. In *IEEE Virtual Reality 2004* (pp. 149-286). IEEE.

Zeltzer, D. (1992). Autonomy, interaction, and presence. *Presence: Teleoperators & Virtual Environments*, *1*(1), 127-132.

Zhang, R. (2007). Design of Head mounted displays. Retrieved from https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/10/Design-of-head-mounteddisplays-Zhang.pdf

Zimmons, P., & Panter, A. (2003, March). The influence of rendering quality on presence and task performance in a VE. In *Virtual Reality, 2003. Proceedings. IEEE* (pp. 293-294). IEEE.

Appendix A: Overview of Virtual Environments

1. The Origins of the Technology

Modern VE displays builds on a long list of predecessors, and as such, researchers do not agree on a single origin point of the technology. Instead, depending on the criteria one uses to define a "virtual environment," candidates for the first VE display arguably include Wheatstone's Stereograph (Wheatstone, 1838), Link's Flight Trainer (Link & Kail, 1944), Heilig's Telemask or Sensorama (Heilig, 1998), or Sutherland's Sword of Damocles (Sutherland, 1968). Several researchers have dated the foundations of modern VEs even further into history. For example, Lastowka and Hunter (2004) posit that "the history of visual virtual worlds arguably dates back at least to cave paintings" (p21) and several others have reaffirmed similar notions (e.g., Cutting, 1997; Ellis, 1991; Lombard & Jones, 2015; Sheridan, 1993).

While it is interesting to consider the history of VEs, which others have done at length (e.g., Bown et al., 2017; Ijsselsteijn, 2003; Mazuryk & Gervautz, 1996), there is no distinct origin point for VE technology, given the inherently additive and iterative process of technological development. Therefore, instead of reviewing the extended history of VEs from cave paintings forward, I review three common modern VE displays: 1) monitor-based, 2) CAVEs (Cave Automatic Virtual Environments), and 3) HMDs (head-mounted displays). Given the focus of my academic background and this dissertation work, I focus the discussion of VE displays specifically on their usefulness for psychological research.

2. Monitor-Based VEs

Monitor-based VE systems present a computer-generated VE on a display monitor (Tarr & Warren, 2002). For example, a desktop computer with monitor would comprise a monitor based VE, as would a gaming console with a television. While the term *desktop VE* is common in prior literature (see Barfield et al., 1999; Whitelock et al., 2000), the term is misleading given the advances in VE technology (available beyond traditional *desktop* computers). As such, I use the term *monitor-based display* to encompass this broader range of systems: VEs displayed on a monitor (desktop computer with monitor, gaming console with television, smartphone, etc.).

Monitor-based VEs offer several advantages to the researcher. First, the existing user bases of existing monitor-based VEs offers a compelling advantage, for example, Linden

Lab (2013) report that *Second Life* had 38 million accounts and over one million unique monthly users. The size of the available user base, paired with preexisting user organizations (e.g., online forums), can provide the researcher with a large, accessible, international, and often cost-free participant sample. For example, in their survey of *Everquest* users, Castronova (2001) posted on two popular online forums and, within two days and without any compensation for participants, collected more than 3,600 participant responses. Cole and Griffiths (2007) provide a similarly notable example, given that they collected survey data on a diverse range of over 900 users (of various online VEs) across 45 countries. Other researchers have likewise demonstrated this recruiting advantage of monitor-based VEs (e.g., Griffiths et al., 2004; Schiano, 1997). A second major advantage is that monitor-based VEs are often rich in behavioral complexity: virtual economies are sophisticated and intricate (Castronova, 2001), users can develop complex interpersonal relationships (Turkle, 1994), and the VE experience can itself affect the users' behavior (e.g., Yee & Bailenson, 2007). The intricacies of monitor-based VEs imbues them with an abundant source of research potential, and further, the sheer complexity of certain monitor-based VEs (e.g., *Second Life*) are not yet available in CAVE-based or HMD-based VEs.

The core disadvantage of monitor-based VEs for research is that they often do not elicit as strong a sense of virtual presence as do fully immersive displays, such as HMDs. This is problematic for the researcher given that, without virtual presence, the participant's behavior in the VE may not generalize to the real-world setting. Similarly, monitor-based VEs are ill-suited for researchers and clinicians who are interested in applied VEs (e.g., VRET), given that many applied VEs are efficacious when virtual presence is maintained. A final disadvantage is that monitor-based technologies are comparatively old, especially in such a rapidly evolving domain, and today's cutting-edge research is often focused on fully immersive display technologies.

3. CAVEs

The Cave Automatic Virtual Environment (CAVE) is a VE display medium and apt reference to Plato's (c.375 B.C.) Allegory of the Cave (Cruz-Neira et al., 1992; Cruz-Neira et al., 1993). The CAVE consists of four ten-foot by ten-foot screens which surround the user within three walls and a floor (Trika et al., 1997). The CAVE uses a rear-projection system which projects the VE onto each screen surface from the side opposite that of the user, minimizing the shadow caused by the user's silhouette (Cruz-Neira et al., 1993). It is worth noting that in this section I refer to the original CAVE system (see Cruz-Neira et al., 1992); other researchers have applied CAVE phrasing more generally to describe CAVE-inspired systems such as the *CyberSphere* (Ijsselsteijn, 2005), *InfinityWall* (Czemuszenko et al., 1997), *ImmersaDesk* (Czemuszenko et al., 1997), and *NAVE* (Jensen et al., 2000).

The CAVE have several notable advantages for the researcher. First, in terms of visual immersion, the CAVE offers a middle ground between monitor-based displays and HMDs; it is more immersive than a monitor-based VE but does not fully occlude the real world as does a HMD (Buxton & Fitzmaurice, 1998). The CAVE also depicts stereoscopic depth cues (Cruz-Neira et al., 1992), which is an advantage over monitor-based VEs. Second, the CAVE allows physically co-located users to interact in the VE simultaneously (Cruz-Neira et al., 1993). Third, the CAVE employs head tracking but rarely induces the symptoms of simulator sickness common to head-tracked HMDs (Cruz-Neira et al., 1993).

Unfortunately for advocates of the CAVE, many of the above attributes are double-edged. For example, though the CAVE allows multiple co-located users to physically interact, the visual scene updates only to a single user's head movement (Czernuszenko et al., 1997), which can result in a passive and unsatisfactory experience for additional users. Similarly, multiple users in a CAVE can physically occlude one another's view of the VE (Buxton & Fitzmaurice, 1998). The user's sense of virtual presence is also particularly fragile in a CAVE system, given that their sense of virtual presence can precipitously break upon noticing the open-real wall or open ceiling (Razzaque et al., 2002). The final disadvantage to a CAVE system is its impracticality for many researchers, given that the system is expensive, hardware intensive, fragile, and the projection-based VE is subject to environmental light interference (Cruz-Neira et al., 1993).

4. HMDs

A HMD is a display the user wears on their head, as one would wear a helmet (Buxton & Fitzmaurice, 1998). The visual display within modern HMDs is often comprised of two separate screens, one positioned in front of each eye, to display slightly disparate images of the scene and portray binocular depth cues (Geng, 2013). Generally, HMDs fully immerse the user's vision (Buxton & Fitzmaurice, 1998) and often employ a head tracking system (Raja et al., 2004; Sutherland, 1968)

A primary advantage of a HMD is its ability to induce stronger feelings of virtual presence compared to other systems (Fox, Arena, et al., 2009), which is important for the reasons noted just above (result generalizability, efficacy with applied VEs, etc.). The decreasing cost of HMDs is a second advantage to the researcher. As a reference, the U.S. Congress (1994) Office of Technology, writing in 1994, cited the cost of a then high-end HMD (60˚ field-of-view, 1280 x 1024 pixels, weighing 4.5 pounds) at $145,000. The cost of a commercial HMD today, with similar specifications, and in many ways improved specifications, can cost less than $1,000. The increasing prevalence of commercially available HMDs, designed specifically for a widespread consumer user base, also implies that the HMDs are hardy, mobile, intuitive to use, and compatible with existing VE content and software; these attributes benefit consumer and researcher alike.

The primary disadvantage while using a HMD in research is its high rate of simulator sickness compared to other systems (Howarth & Costello, 1997; Sharples et al., 2007). Simulator sickness can be particularly problematic from a researcher's perspective given the potential for high participant drop-out (e.g., Balk et al., 2013; Sharples et al., 2007; Stanney et al., 2003). A study which induces simulator sickness has the obvious distaste of causing discomfort to participants, who are volunteering their time to participate in the research. Simulator sickness, if unaccounted for, can also be a methodological threat, given that simulator sickness may affect the variable of interest (e.g., task performance) and a high drop-out rate could threaten the generalizability of findings (e.g., a survivor bias).

Appendix B: HMD Components and Auxiliary Technologies

1. Primary System Components

In general, four major components comprise a HMD-based VE: 1) a tracking system, 2) a graphics engine, 3) a visual display, and 4) an application host (Mine, 1993).

The tracking system is responsible for gathering information on the user's head location (often by identifying headset sensors) and limb position (often by identifying sensors in hand-held controllers) (Mine, 1993). Though there are various tracking technologies (magnetic, mechanical, infrared, sonic, etc.) the goal of each is the same, to track user limb position accurately and with minimal latency (Mazuryk & Gervautz, 1996).

The graphics engine refers to the computer hardware required to update, process and transmit the computer-generated VE to the display medium (Mine, 1993). An important consideration regarding the graphics engine is the level of VE visual scene detail, often expressed as the number of polygons which comprise the virtual world (Mazuryk & Gervautz, 1996). A highly detailed VE will consist of a higher number of polygons, and subsequently, it will require a higher quality graphics engine to update the scene at a sufficient frame rate (Mazuryk & Gervautz, 1996). Generally, researchers consider 30 frames-per second to be the minimally acceptable frame rate for a VE (Barfield et al., 1998; Salisbury & Srinivasan, 1997).

The visual display is the physical interface that the user views, which in the case of a HMD, is often a pair of monitors (one for each eye) (Mine, 1993). The visual display has two key specifications: resolution and field-of-view. Resolution refers to the display acuity, defined by the number of vertical and horizontal pixels which make up the screen (e.g., 1200 x 800 pixels), whereby a higher pixel density indicates higher visual detail (Geng, 2013). The second key dimension, field-of-view, is the amount of the VE that a user can view at a time while their head is stationary (Barfield et al., 1990).

The final component in this high-level overview is the application host. The application host is a computer which coordinates the processing of the tracking system, the graphics engine, and the visual display (Mine, 1993). In essence, the application host manages the information from each of these prior components, and acting as a data manager, synchronizes them together (Mine, 1993).

2. Auxiliary System Components

In addition to the primary components above, I review three supporting technologies given their prevalence in the literature: 1) stereoscopic displays, 2) haptic interfaces, and 3) locomotion support systems.

2.1. Stereoscopic Displays

As many researchers note, the ability to portray stereoscopic depth cues is an important aspect of a visual display (Freeman et al., 1999; Geng, 2013; Sutherland, 1968; etc.). Stereoscopic depth in a VE display can enhance user visual perception (Kline & Witmer, 1996), improve VE task performance (Barfield et al., 1999), and increase the experience of virtual presence (Freeman et al., 1999).

Our perception of stereoscopic depth, in both unmediated vision and with a stereoscopic HMD, results from the lateral disparity of the human eyes (Geng, 2013). Adult pupils are 63 millimeters apart on average (Howarth, 1999), and because of this interpupillary distance, each eye receives a slightly different retinal image (Cutting, 1997). These disparate retinal images (known as stereo pairs) form the basis of human binocular depth perception (Geng, 2013). During visual processing, the stereo pairs fuse into a single percept along the horopter line of focus (Cutting, 1997; Lambooij et al., 2007) and during this fusion the brain acquires a powerful depth (Cutting & Vishton, 1995). Stereoscopic depth cue is a powerful depth cue within approximately 30 meters, beyond which the eyes diverge to such an extent that the retinal images are effectively identical and monocular cues become the primary indicators of depth (Cutting, 1997; Cutting & Vishton, 1995).

The research on stereoscopic vision is rich historically, and many famous scholars (e.g., Euclid, Galen, and Leonardo da Vinci) receive credit for acknowledging the existence of stereo pairs in their own work (see Brewster, 1856; Cutting, 1997). The achievements of these predecessors notwithstanding, one could argue that modern displays most owe credit to Wheatstone (1838), who both identified the underlying process of human stereopsis and created the first stereoscopic visual display (the Stereoscope).

Modern stereoscopic displays adhere to the same principles as Wheatstone's (1838) Stereoscope, but use one of three modern methods: 1) a color-interlaced technique, 2) a time-multiplexed technique, or 3) a dual-streamed technique (Geng, 2013). Color-interlaced displays create a retinal disparity by presenting two partially overlapped (interlaced) images on a screen, each with a different color hue (Geng, 2013). In order to view a single image in three-dimensional depth, the user wears color-tinted glasses with each lens corresponding to, and filtering out, a respective image hue. By wearing the glasses, each eye receives a single retinal image of the stereo pair which then fuse into a single three-dimensional percept (Geng, 2013); “3-D” movies, where viewers wear “3-D glasses,” is an extremely common example of the color-interlaced technique at work.

Time-multiplexed displays, which Cruz-Neira et al. (1992) use in their CAVE, rely on shutter-glasses. Shutter glasses are goggles, worn by the user, which rapidly open and close each eye’s lens in alternating succession (Geng, 2013). As the glasses shutter to occlude each eye successively, the visual scene likewise alternates between two slightly different images of the scene, so that each eye receives its respective retinal image for stereo fusion (Geng, 2013). Shutter-glasses afford stereo fusion by taking advantage of the human visual system’s ability to fuse temporally separated images within a 50 millisecond threshold (Meesters et al., 2004). Modern time-multiplexed displays meet this threshold by a sizable margin, for example, Sony (2011) 3-D Television, which uses shutter glasses, presents each retinal image just five milliseconds apart.

Though CAVE displays use a time-multiplexed technique, modern HMDs most often use a dual-streamed technique (Geng, 2013). Dual-streamed displays consist of two separate screens which display a continuous and slightly different video stream to each eye (Geng, 2013). The accuracy of Wheatstone’s (1838) visual perception work and the effectiveness of his original Stereoscope is evident when considering dual-streamed displays, given that a dual-streamed display is effectively a Wheatstone Stereoscope with updating images.

2.2. Haptic Interfaces

A haptic interface (or haptic input device) is a device which allows the user to interact with objects in the VE through touch, for example, a hand-held controller is a haptic input device. Further, haptic interfaces often provide tactile sensations (e.g. vibration) and kinesthetic feedback (e.g., limb position via handheld controller) to the user (Haans & Ijsselsteijn, 2006). The user’s sensory experience of a VE would be severely restricted without a haptic interface, as Reiner (2004) states, without haptic interaction the user’s experience would have “the feel of a dream, being able to see, but often paralyzed and unable to act” (p398).

Researchers have employed a range of haptic interfaces to date, including computer mice, force-feedback joysticks, hand-held controllers, and user-worn gloves (Haans & Ijsselsteijn, 2006; Srinivasan & Basdogan, 1997; Stoakley et al., 1995; Wilson & D'Cruz, 2006). These haptic interfaces afford the user various VE actions, including object manipulation, viewpoint control, and system control tasks such as menu navigations (Bowman, 1999). Additionally, researchers have discussed several useful VE interaction metaphors, all of which require a haptic interface to implement, these include *Ephemeral World Compression* (Tan et al., 2001), *Go-Go Interaction* (Poupyrev et al., 1996), *Heaven and Earth* (Fairchild et al., 1993), *HOMER* (Bowman, 1999), *Virtual Ray Casting* (Poupyrev et al., 1997) and Worlds in Miniature (Stoakley et al., 1995).

2.3. Locomotion Support Systems

A locomotion support system is a technology or technique in which physical user action translates into the appearance of VE movement. It is often the case that the VE is much larger than the physical space surrounding the user and so the user requires a method of simulated movement to navigate the virtual world. I classify locomotion support systems as natural systems or simulated systems.

Natural locomotion support systems rely on a natural pattern of walking movement to create the appearance of movement within the VE. For example, walking-in-place, redirected-walking, reorientation, and arm-swinging techniques would each constitute a natural locomotion support system (Boletsis, 2017). Other natural locomotion support systems are less practical. For example, the *Omni-Directional Treadmill* offsets physical forward movement with 12 custom treadmills (Darken et al., 1997), while the *HIVE* uses a 572 square-meter room, eight tracking cameras, and a separate control room (Waller et al., 2007). This said, a natural locomotion support system, if practical, is advantageous given that natural walking motions are intuitive (Iwata, 1999), afford hands-free travel (Darken et al., 1997), and tend to enhance user virtual presence (Schuemie et al., 2005).

Simulated locomotion systems rely on a haptic interface, in which the user initiates virtual movement with a hand-held device. For example, VEs often rely on controller-based locomotion whereby the user pushes forward on a controller joystick or thumb-pad to initiate simulated forward movement in the direction of their gaze (Boletsis, 2017). Though the user is not physically engaging in a walking motion, simulated locomotion provides a compelling sensory experience which can prompt users to lean and sway as if they were physically moving (Ijsselsteijn et al., 2002). The comparative ease of using a simulated locomotion technique, paired with evidence supporting the perceived realism of movement, makes it a useful alternative for VE navigation.

Appendix C: VE Applications

1. Introduction

In this review of VE applications I take a relatively high-level view of the literature, in that I focus on general application categories (e.g., "training") and I primarily discuss the advantages of VE technology for each category. I focus on the advantages for several reasons. First, I discuss the limitations and challenges to VE technology at length elsewhere (e.g., Appendix D; Appendix E; Appendix F). Second, the advantages of applied VEs tend to generalize across studies (e.g., increased motivation with VE-based trainers) while the limitations in the research tend to be case-specific (e.g., small study sample size). Third, detailing the nuance of the applied VE literature for each category (including the associated benefits, limitations, conditions, and contexts of the research) would warrant a lengthy series of reviews which would digress far beyond my core focus (virtual presence).

2. Teleoperation

Teleoperation, in which a remote worker affects a physically distant site through robotic manipulators, is one of the earliest applied uses of VE technology (Draper et al., 1999; Johnsen & Corliss, 1971; Minsky, 1980). Though teleoperation systems do not always use a computer-generated VE, they do employ traditional VE display systems (e.g., stereoscopic HMDs) and often overlay virtual objects and superimposed information to the operator (Mazuryk & Gervautz, 1996). Teleoperation is also important to mention given its historical importance in the virtual presence literature, as authors credit the pioneers of teleoperation research (Johnsen & Corliss, 1971 and Minsky, 1980) with coining the term presence (Coelho et al., 2006; Ijsselsteijn et al., 2000; Sas & O'Hare, 2003a; etc.).

Teleoperation systems rely on an operator viewing and manipulating a remote physical environment (Robinett, 1992), which is especially useful if the worksite would be hazardous to on-site operators (Minsky, 1980). For example, Anderson et al. (1997) describe the Virtual-Window Project, in which a teleoperator dismantled a nuclear reactor at a safe physical distance. Because researchers often discuss teleoperation in the context of such high-risk work, Durlach (1997) argues that teleoperation has an "overly serious, unimaginative" (p352) reputation. Acknowledging Durlach's point, it is worth noting that teleoperation systems have a wide range of applied use cases, including the operation of unmanned vehicles, remote-controlled toys, and remote camera controls. Unmanned aerial drones are perhaps the most common teleoperation systems today, and according to Meola (2017), over two million aerial drones sold in the U.S. alone in 2016 (more than double the number sold the year prior). The proliferation of unmanned aerial drones, though a relatively nascent teleoperation technology, has profound implications for the agriculture, entertainment, research, and defense industries (Estes, 2013).

An important consideration in teleoperation, across its many applications, is the experience of operator telepresence. Schloerb (1995) suggests that operator telepresence has two dimensions: objective telepresence and subjective telepresence. Objective telepresence is a metric of task performance, referring to the operator's ability to successfully affect the remote physical environment (Schloerb, 1995). Subjective telepresence refers to the operator's subjective sense that they are spatially located at the remote physical site (Schloerb, 1995). Given that the primary goal of teleoperation is the successful manipulation of a remote physical location, teleoperation research tends to focus on objective telepresence (Durlach, 1997; Johnsen & Corliss, 1971). This emphasis is due in part to the still disputed importance of subjective telepresence, regarded by some as an epiphenomenon (Ellis, 1996) and by others as an important factor in operator workload reduction (Draper et al., 1999). Further research could illuminate the role of subjective telepresence, if any, in teleoperation.

3. Education

Educators are employing VEs as a teaching tool across education levels (e.g., Bayon et al., 2003; Seymour et al., 2002). For example, in early education research, experimenters have demonstrated that VEs enhance student learning of teamwork (Roussos et al., 1997), reading (Bayon et al., 2003), and zoology (Allison et al., 1997). Among high school and university students, Brelsford (1993) demonstrated that a physics lecture given with a VE aid resulted in higher learning and higher long-term retention, compared to a standard lecture. Among surgical residents in medical school, Seymour et al. found that residents in the VE learning group completed their surgical exam 29% faster and with 17% the errors of the traditional learning group.

The effectiveness of VE teaching aids is certainly due in part to the technological affordances of the VE display, which can provide the student a multisensory experience of abstract or difficult to visualize concepts (Freina & Ott, 2015). Additionally, VEs tend to be more engaging than traditional teaching techniques, which Chang (2009) suggests enhances both student interest and student learning motivation. A final benefit is that VEs, and especially immersive VEs, can induce a sense of virtual presence, which according to Whitelock et al. (2000), further enhances student motivation to learn course material.

4. Training

VEs are an effective workplace personnel training tool with several unique benefits. First, VE training is critically important to train personnel on tasks which are complex, dangerous, or expensive to teach in the real world (Anderson et al., 1997). Second, VEs are highly manipulable, in that the trainer can control environmental factors, repeat exact scenarios, and easily record trainee performance for follow-up review (Loren, 2012). Third, VEs enhance trainee buy-in, whereby the trainee is more motivated to accept a 'training mindset' and spend more time practicing the desired skillset (Alexander et al., 2005). Finally, VEs (and particularly immersive VEs) can elicit a strong sense of virtual presence, which is considered essential for transfer of training from the virtual to the real world (Fox, Arena, et al., 1999).

Given these advantages it is unsurprising that researchers have thus far demonstrated that VEs can enhance the training of a variety of personnel, including aircraft fault inspectors (Vora et al., 2002), emergency responders (Youngblut & Huie, 2003), pilots (Carretta & Dunlap, 1998), soldiers (U.S. Congress, 1994), and surgeons (McCloy & Stone, 2001).

While there are ample examples of VE training, the U.S. Department of Defense's (DoD) long history with VE technology (U.S. Congress, 1994) makes it an exemplar of VE-based training. The DoD's interest in VE training dates to their purchase of the Link Trainer, a mechanical flight simulator, in the 1930s (De Angelo, 2000; U.S. Congress, 1994). The Link Trainer was especially prevalent during World War II, when the DoD purchased approximately 10,000 Link Trainers to reduce the training time for over 500,000 pilots (De Angelo, 2000). The U.S. Congress (1994) estimates that, in a single year alone, the Link Trainer saved hundreds of lives, 30 million work-hours, and hundreds of millions of dollars in training costs. The success of the Link Trainer propelled researchers to develop future VEs for a wide range of military domains (Darken et al., 1996; Lampton et al., 1995; U.S. Congress, 1994). The DoD continues to use VEs in its training, including to train vehicle rollover protocol (Wells, 2010), combat communication (Loren, 2012), shooting (Chang,

2009) and close quarter combat with vehicle support (U.S. Army, 2010). The continued success of modern VE training is clear, for example, the implementation of the HEAT (vehicle rollover) simulator has increased the survival rate of actual vehicle rollovers by 250%; the HEAT simulator is now mandatory pre-deployment training for all U.S. airmen, sailors, army infantry, and marines (Wells, 2010). Another notable modern VE trainer is the Engagement Skills Trainer (EST), which trains weapons safety and targeting for almost every military firearm (Chang, 2009). The EST simulates live fire, provides real-time feedback, and records trainee skill progression (U.S. Army, 2019); the EST has been obviously successful, as since its introduction, the U.S. Army has purchased an additional 700 EST simulators (U.S. Army, 2010). The U.S. Army (2010) has announced plans to increase its use of VE trainers and, at time of writing, is developing VEs for Combined Arms Training Strategies (CATS), Dismounted Soldier (DS) training, and Sergeant Time Training (STT).

5. Industrial Design and Process Improvement

There are many examples of professionals using VEs in workplace applications, for example, in supporting worker factory-line assembly (Boud et al., 2000), product prototyping (Cobb et al., 1995), process planning (Mujber et al., 2004), and data visualization (Wilson & D’Cruz, 2006). There are many similar examples cited in the literature (Wang, 2002; Seth et al., 2011), and further, VE design applications are increasingly commonplace in industry (e.g., McIntosh, 2017; Pepitone, 2016).

Industry professionals are increasingly using VEs technology in the workplace given several key advantages. First, industrial prototyping and design applications benefit from stereoscopic depth cues (often available in HMDs), as well as the comparatively natural interaction techniques (with haptic input devices) compared to traditional design softwares (Trika et al., 1997). For example, with an immersive stereoscopic display, the designer can better view and understand the ergonomics, relative dimensions, and visual aesthetics of a product’s design (Wang, 2002). Second, immersive displays are useful while planning industrial tasks; an immersive VE allows the engineer to better anticipate product assembly tasks by allowing them to view parts from different angles, view available tool clearances in a virtual workstation, simulate product assembly in a VE, and better assess potential points of assembler injury (Seth et al., 2011; Wang, 2002). Finally, researchers note that virtual prototype evaluation is often faster and less expensive than evaluating and iterating physical prototypes (Wang, 2002; Seth et al., 2011).

6. Workplace Communication

Though today email is likely the most popular office communication technology, in certain contexts, employees may soon prefer immersive VEs for workplace communication. While email has practical advantages, the technology limits the effectiveness of interpersonal communication. Mehrabian and Ferris (1967) state that interpersonal communication is primarily non-verbal, whereby our word choice comprises only a fraction of the overall message. Emailed communication, which is largely devoid of non-verbal cues, suggests that valuable information is being lost or miscommunicated. From a business perspective, the cost of such workplace miscommunication can be immense, for example, a survey of large corporations found that office miscommunication cost each, on average, $62.4 million annually (Holmes Report, 2011).

An emerging VE application which could enhance workplace communication is the Collaborative Virtual Work Environment (CVWE) (Benford et al., 2001). In the literature, CVWEs have slightly different terminologies (e.g., Collaborative Virtual Environment) and differing definitions (see Pinkwart & Oliver, 2009), however, Benford et al. (1995) provide an overview of a CVWE exemplar. Benford et al. (1995) describe a CVWE as a virtual a conference room, in which remote employees, collocated in the VE through their avatars, can speak, convey non-verbal gestures through their avatar, and view or manipulate shared data (e.g., a presentation) simultaneously. This type of virtual conference room offers remote employees substantial benefit. A CVWE allows distant employees to communicate naturally (i.e., verbally and non-verbally), which researchers suggest would enhance remote meeting efficiency and collaboration (Cruz et al., 2014; Churchill & Snowdon, 1998). Further, Biocca and Levy (1995) suggest that a CVWE could augment interpersonal communication in ways that are not possible through existing communication mediums or the real world; as an example, the authors suggest CVWE mood augmentation, where a frowning user's avatar turns blue to clearly signal their emotional state to others. Another useful augmentation would be a question mark appearing above a confused user's avatar, which could prove useful in a variety of professional and educational contexts.

Given that a CVWE could emulate or enhance remote communication, the technology could also reduce the necessity and cost of business travel. The Global Business Travel Association (2018) reports that the aggregate cost of business travel in 2016 was $1.3 trillion, an amount more than double the $634 billion spent in the year 2000 (Global Business Travel Association, 2018a). Analyst expect that business travel expenses will continue to increase into the future (Global Business Travel Association, 2018a). A CVWE, in which remote employees feel social presence (i.e., genuinely co-located in a shared space) could obviate business travel. Ijsselsteijn, Harper, et al., (2001) and Kircherr and Biswas (2017) extend this argument to professional conferences, suggesting that VE-based conferences would be a convenient, affordable, and perhaps preferable, alternative.

7. Social Sciences Research

Academics are increasingly using VE technology as a research tool, an especially prevalent trend in social sciences research. For example, psychologists have used VEs to investigate topics such as clinical disorder symptomology (e.g., Freeman et al., 2003), psychomotor action (e.g., Mason et al., 2001), distance perception (e.g., Kline & Witmer, 1996), interpersonal social dynamics (e.g., Bailenson & Yee, 2008), and reality judgment within a VE (e.g., Usoh et al., 2000).

The prevalence VEs in social science research is certainly due, in part, to the unique methodological advantages that a VE provides to the researcher. An initial advantage is the high degree of experimental control, in that the researcher has complete control in programming the VE and therefore can mitigate the influence of extraneous variables to strengthen internal validity. Additionally, measuring the participant's experience of virtual presence provides a measure of ecological validity, given that virtual presence implies that the participant's virtual behavior reflects their real world behavior (Fox, Bailenson, et al., 2009). A final advantage is that, using a VE, the researcher can investigate scenarios that would be dangerous, expensive, or physically impossible to produce in the physical world. These methodological advantages are profound, and as such, it is likely that VE methods will become increasingly commonplace in social sciences research.

8. Pain Management

To date, doctors have successfully used VEs in patient pain-management for multiple conditions (Gershon et al., 2004; Hoffman et al., 2000; Li et al., 2011). In their review, Li et al. (2011) report that the empirical evidence generally supports that VEs are an effective tool to reduce both patient pain and patient pre-procedure anxiety; Dascal et al. (2017) and Malloy and Milling (2010) in their own reviews of the literature arrive at similar conclusions. The efficacy of VE pain management is especially promising when considering the common practice of using pharmacological (e.g., opiate-based) pain treatments, which are difficult to administer, ineffective in treating certain conditions, and susceptible to patient abuse (Centers for Disease Control, 2019; Das, 2018; Hoffman et al., 2000). Highlighting the optimism around this application, Das suggests that VE pain management could supplement (or replace) opiate-based treatments for many conditions; Li et al. (2011) add that VEs may be suitable beyond clinical settings, and could be a suitable at-home pain treatment. The growing interest and optimism in this domain is demonstrably clear, for example, the number of NIH-funded studies on VE pain management doubled in 2011 compared to 2010 (Li et al., 2011).

9. Physical Rehabilitation

In a related medical application, VEs show promise as a physical rehabilitation aid (Henderson et al., 2007). VE physical rehabilitation aids often take the form of interactive games, which encourage the patient to move, stretch, and balance to regain lost physical mobility (Kizony et al., 2005). VE physical rehabilitation aids show promise for even the most severe injuries, for example, Sveistrup et al. (2003) demonstrated the efficacy of a VE rehabilitation aid for patients with balance disorders following traumatic brain injury. Similarly, Kizony et al. (2005) used a VE rehabilitation aid with patients recovering from paraplegic spinal cord injuries. While VEs appear useful in physical rehabilitation, more research is necessary prior to drawing steadfast conclusions, as researchers often note that small sample sizes and methodological limitations challenge the generalizability of existing results (Henderson et al., 2007; Parsons et al., 2009).

10. Psychological Treatment

Academics and clinicians use VEs while researching and treating a wide array of mental health outcomes and symptomologies, including autism spectrum disorder (Newbutt & Donogon, 2010), dementia (Flynn et al., 2003), dyslexia (Kalyvioti & Mikropoulos, 2014), eating disorders (Gutierrez-Maldonado et al., 2006), persecutory ideation (Valmaggia et al., 2007), nicotine cessation (Lee et al., 2004), schizophrenia (Ku et al., 2003), and various phobias (Gregg & Tarrier, 2007).

Though psychologists use VEs in a range of clinical applications, arguably the most common application is virtual reality exposure therapy (VRET) (Gregg & Tarrier, 2007). In general, exposure therapy is a phobia treatment in which the client is gradually introduced to the aversive stimuli (e.g., a spider) over a series of progressing trials (Parsons & Rizzo, 2008). According to Parsons and Rizzo, exposure therapy has three primary delivery methods: in-vivo exposure (e.g., an exposure to a real spider), imaginal exposure (e.g., visualizing an exposure to a spider), and recently, virtual exposure (e.g., an exposure to a computer-generated spider while in a VE). Though in-vivo and imaginal exposures have longer histories of use, researchers have found that VRET is an effective treatment alternative (Parsons & Rizzo, 2008). Since the earliest VRET treatment for acrophobia (Hodges et al., 1994), clinicians have treated clients with aerophobia (Rothbaum et al., 2002), arachnophobia (Carlin et al., 1997), acrophobia (Emmelkamp et al., 2002), agoraphobia (Viaud-Delmon et al., 2006), cynophobia (Taffou et al., 2012), anorexia nervosa (Gutierrez-Maldonado et al., 2006), driving phobia (Walshe et al., 2003), and others (Gregg & Tarrier, 2007).

The rapid growth and wide range of VRET applications is unsurprising considering the empirical evidence to date: VRET is effective in reducing phobic responses (Botella et al., 2017; Oing & Prescott, 2018), more effective than imaginal exposure (Alsina-Jurnet et al., 2007), and as effective as in-vivo exposure (Emmelkamp et al., 2002). Parsons and Rizzo (2008) note the success of VRET in their meta-analytic review on the topic, concluding that "VRET had statistically large effects on all affective domains, as well as all anxiety/phobia groupings evaluated" (p256).

Appendix D: VE Legal Challenges

1. Introduction

The scope of modern VEs, which afford increasingly complex interactions among thousands of users in real time, raises uncharted legal questions. Scholars are aware of the legal complexity surrounding today's VEs, and jurists are actively discussing if (and how) past precedents apply to virtual worlds (Lastowka & Hunter, 2004; Lemley & Volokh, 2018). For example, court systems have heard disputes regarding VE harassment (Buchleitner, 2018), VE avatar 'murder' (New York Times, 2008), VE property theft (Lastowka, 2012), and VE copyright infringement (Heath, 2017). These virtual crimes carry real consequences, for example, the avatar murderer (who deleted the virtual avatar of another user) faced up to five years in prison (New York Times, 2008) while a recent case of VE copyright infringement ended in a $500 million settlement (Heath, 2017). Though the legal discussion regarding VEs covers a range of topics, I focus on two legal issues based on the work of Lemley and Volokh: 1) virtual street crime and 2) virtual property ownership.

2. Virtual Street Crime

Virtual street crime encompasses malicious actions between VE users, including cases of harassment, lewdness, and virtual assault (Lemley & Volokh, 2018). Further, by looking at user conduct in current online communications (e.g., online forums) one can reasonably foresee cases of VE cyberstalking, threats of physical harm, and the intent to cause physical harm through the medium (Pittaro, 2007; Miller, 2017; Roberts, 2017).

Virtual street crime is particularly important in HMD-based VEs, where user virtual presence tends to be higher than in monitor-based displays (e.g., Zanbaka et al., 2004). The experience of virtual presence can magnify the negative effects of virtual street crime as "the more visceral VR [virtual reality] becomes, the more it feels to the victim like a real assault" (Lemley & Volokh, 2018, p31). There is empirical evidence corroborating this notion, as researchers have repeatedly demonstrated that virtual presence heightens one's perception that a virtual danger can cause personal harm (Slater, Usoh & Steed, 1994; Slater, Usoh & Steed, 1995; Zimmons & Panter, 2003). Relatedly, research on the Rubber Hand Illusion demonstrates that participants can misperceive an artificial limb as an extension of their own body and embody the limb into their own body schema (e.g., Botvinick & Cohen, 1998). Petkova and Ehrsson (2008) report that the Rubber Hand Illusion generalizes to an entire artificial body, and further, that threatening the artificial body causes heightened physiological stress, as if the participant them self (and not the artificial body) were being threatened with bodily harm. The visual-tactile sensory matching which produces the Rubber Hand Illusion (embodiment of an artificial body) foreseeably replicates with the visual-tactile sensory matching in a VE (embodiment of a virtual avatar), and so the same visceral fear of bodily harm would also generalize.

Though VE users may experience virtual harassment, threats, or authentically perceive that they are in danger, the question of legally punishing a virtual crime is complex. In short, it is unclear what VE actions constitute a criminal offense. Legal decisions in similar media could inform the future, for example, cyber-stalking is a criminal offense in most U.S. states, punishable with fines or incarceration, while threatening physical harm online is a federal offense (Pittaro, 2007). It is reasonable to assume that lawmakers will treat cyber-stalking and digitial threats similarly in a VE. However, regardless of the law, there remains what Lemley and Volokh (2018) call the *Bangladesh Problem*, which describes the difficulty in enforcing a law when the parties are in geographically distant locations. The Bangladesh Problem is two-fold: authorities must physically locate each party and then prosecute an offender despite differences in legal jurisdictions (Lemley & Volokh, 2018). Lemley and Volokh and Pittaro both note this problem with existing digital, given that user defamation, release of private information, threats of bodily harm, cyber-stalking, and related online crimes, usually occur without legal repercussion.

3. Virtual Property Ownership

VEs commonly allow users to earn virtual currency, buy and sell virtual goods, and trade virtual property with other users (Castronova, 2001). Though VE items have little tangible worth, users are increasingly spending real world money on VE items. The growth of this practice is remarkable. For example, the users of Ultima Online spent an estimated $3 million on virtual items (Dibbell, 2003), a sum dwarfed a short time later by the users of Second Life, who spent an aggregate $3.2 billion over a ten year period (Linden Lab, 2013). More recently, the users of Fortnite spent an estimated $1.8 billion in aggregate on VE purchases in 2019 alone (Neilsen Group: Super Data, 2020).

Despite the increasingly common practice of purchasing VE items with real world money, a basic question remains: does the user own the VE item that they purchased? A simple answer is that the VE creator, often a corporation backed by an end-user licensing agreement, is the sole owner (Lemley & Volokh, 2018). This answer would imply that the virtual item has no legal significance for the user, who therefore cannot litigate (Herzfeld, 2012). The fact that users spend money on virtual items challenges this deceptively straight forward answer (Lastowka & Hunter, 2004). As Herzfeld argues, players who spend real world money in a VE have a reasonable expectation of ownership, which may provide legal significance. Additionally, Herzfeld argues that treating virtual objects as legally non-significant (i.e., corporation owned) creates a "complete legal vacuum [in] handling the most basic commercial disputes" (p1). Treating virtual items as legally significant (i.e., user owned) naturally benefits the user, but the practice would cripple the corporation's ability to effectively manage the VE (update items, ban users, etc.) (Herzfeld, 2012). Court rulings to date on virtual property ownership have ruled in favor of both the user and the corporation on different occasions (Muijen, 2015).

An alternative solution is to treat VE items as a form of intellectual property, a legal designation used in the ownership of intangible assets (Lastowka & Hunter, 2004). Unfortunately, this option is likewise subject to dispute given that both the corporation (data owner) and the user (significant modifier of data) meet the legal criteria for intellectual property ownership (Herzfield, 2012). For example, *Minecraft*, a VE in which users enter a virtual world and create environmental objects with individual building-blocks, highlights the issue of an intellectual property designation (Gilbert, 2018; Haridy, 2017). Minecraft users construct elaborate creations, such as a rendition of Medusa comprised of 1.1 million individually placed blocks or a fantastical environment which took 7 billion individually placed blocks (Haridy, 2017). Though the user modified the base environment with creativity and diligence, the corporation provided the platform for creation in the first place, and so the question of intellectual ownership is debatable.

Interestingly, the legal question of VE item ownership is theoretically a non-issue. Unlike the real world, modern VEs can provide each user with effectively unlimited resources which should make the question of ownership a moot point (Lastowka & Hunter, 2004). However, VEs are often like the real world in terms of resource scarcity, and given the observable trends to date, it is likely that the magnitude of user spending (and the associated legal issues) will only increase in the future.

Appendix E: VE Ethical Challenges

1. Introduction

Beardon (1992) argues that the presence inducing nature of VE technology means that "the responsibilities of the author of that reality are no less than the person who administers a consciousness controlling drug, and the ethical principles which that person works under should be no less severe" (p27). While most others are more lenient in tone, researchers commonly discuss the questions and concerns surrounding VE ethics (Beardon, 1992; Brey, 2008; Schulzke, 2010; Sheridan, 1993; Whitby, 1993; etc.).

The discussion around VE ethics often forms around a question of censorship. Content censorship is a longstanding debate across medias (e.g., with literature, film, and television), however, the discussion of VE censorship bears two unique differences from past medias. First, VEs tend to enable a strong sense of virtual presence, in that the user has a visceral experience of the content (Lemley & Volokh, 2018). Second, VE users are active and causal participants in the content, which is a fundamentally different experience from passive viewership. These two factors add complexity to a number of ethical considerations, most prevalent among them are questions of immoral behavioral transfer (Schulzke, 2010), user escapism (Whitby, 1993), addiction (Wilson, 1996), and the effect of VE technology on mental health (Beardon, 1992; Huang & Alessi, 1999). In practice, these concerns manifest as a discussion of VE content censorship.

2. Arguments for VE Censorship

Whitby's (1993) work provides an excellent framework to evaluate the arguments for VE censorship. Whitby suggests that: 1) users who commit immoral virtual acts may do the same in the real world; 2) certain behaviors are inherently unacceptable, even in private media use; 3) users may prefer the virtual over the real world; and 4) without oversight, VE content creators would gain unwarranted power in deciding ethical standards. Of these, I use Whitby's first three arguments to guide the discussion, given that these are the common themes in the literature. I do not address Whitby's fourth point at length, as in practice, regulatory bodies (e.g., the U.S. Federal Communications Commission), and not content creators, set ethical standards and content regulations.

Whitby's (1993) first argument is that immoral user behavior in a VE can transfer to the real world, for example, exposure to virtual violence can cause a user to commit violent acts. This notion has a foundation in the empirical literature. For example, Calvert and Tan (1994) found that users exposed to violent VE content self-report increased aggression following the exposure. Nowak et al. (2008) report similar findings, additionally noting that virtual presence is a moderating factor for the transfer of aggression. Likewise, Anderson et al. (2010) in their meta-analytic review conclude that “the evidence strongly suggests that exposure to violent video games is a causal risk factor for increased aggressive behavior, aggressive cognition, and aggressive affect and for decreased empathy and prosocial behavior” (p151).

Whitby’s (1993) second argument is that certain media content is inherently unacceptable even for private usage. Brey (2008) provides the examples of virtual torture, rape, and murder as unacceptable behaviors, even virtually. Similarly, Brey raises the issue of depicting actual likenesses (e.g., politicians, celebrities, etc.) in a VE, and under what context (if any) such depictions are appropriate. Sheridan (1993) additionally cautions against depicting or allowing users to engage in sexual behaviors in a VE whatsoever, even for private use. While government bodies currently decide on acceptability standards, the decisions can be questionable and highlight the apparent gray areas; Brey notes that the U.S. Supreme Court, citing the first amendment, overruled a congressional ban on certain virtual child pornography (in *Ashcroft v. Free Speech Coalition*, 535 U.S. 234, 2002).

Whitby’s (1993) third argument for VE censorship, that users will prefer the VE over the real world as way of escapism, is a point often made elsewhere (e.g., Kallman, 1993; Mazuryk & Gervautz, 1996; Sheridan, 1993; Wilson, 1996; etc.). The risk of user escapism is obvious, given that a main appeal of a VE is to enter a new world with a new virtual identity. Given a lack of direct empirical evidence, the question of VE escapism remains limited to conjecture, though trends in user smartphone addiction (De-Sola Gutierrez et al., 2016) and internet addiction (Kuss et al., 2014) may presage the future of VE escapism.

3. Arguments Against VE Censorship

Schulzke (2010) provides three core arguments against VE censorship, which I use as a framework to evaluate this alternative viewpoint. Schulzke’s arguments are that 1) user behavior in a VE is fundamentally different than their real world behavior; 2) we should weigh the societal gains from potentially immoral VE content (e.g., economic growth and job creation) against the potential risks; and 3) content censorship inherently denies user decision making and moral growth.

Schulzke (2010) bases the first argument, that VE behavior is fundamentally different than real world behavior, on the premise that the user intuitively understands that virtual behavior does not cause physical harm. As Sanchez-Vives and Slater (2005) argue, when one experiences virtual presence, there is a cognitive awareness that they are in the physical world viewing a display. Whitby (1993) takes this logic further, arguing that the user not only knows that their virtual behavior is physically harmless, but immoral virtual behavior could relieve the urge to commit such behavior in the real world. These arguments imply that, counter to some of the empirical research described above (e.g., Calvert & Tan, 1994), immoral or violent user behavior does not necessarily transfer to the real world. In support of this, researchers have argued that empirical work demonstrating an effect of aggressive behavioral transfer often uses invalid measures, demonstrates small effect sizes, and fails to explain the null relationship between violent media consumption and national crime statistics (Ferguson, 2007; Ferguson, 2010; Schulzke, 2010).

Schulzke's (2010) second argument, citing the popularity of immoral VE content, suggests that regulators should weigh the societal gain during VE production (e.g., job creation) and purchase (e.g., economic growth) against the potential negatives. The societal benefits of VE content creation is observable, for example, through income statistics; employees in the videogame sector earned an average of $97,000 in 2016 (Entertainment Software Association, 2017), 68% higher than the U.S. median income that year (U.S. Census Bureau, 2017). Further, the success of the videogame sector is largely based on immoral (e.g., violent) content; only 11% of videogames produced in 2016 had a "mature" rating (for violence, adult themes, etc.), but these games comprised half of that year's top ten best sellers, including each of the top three (Entertainment Software Association, 2017).

Schulzke's (2010) final argument against VE content censorship is that content regulation denies users the ability to develop their own sense of morality. For example, the VE Bioshock forces its users to decide between harming a child (to rapidly improve their avatar's progress and skillset) or save the child (and develop their avatar more slowly) (Schulzke, 2010). Despite, and perhaps because of, this ability to make moral decisions, Bioshock became widely popular among users and critics alike (King et al., 2010). The same is true of Fallout, which presents users with forced-choice moral decisions which directly affect the user's progress and the storyline (Schulzke, 2010). Turkle (1994) cites *Habitat* as another example, a VE which allowed players to "kill" each other's avatars and steal their items. The morality of player killing was controversial among Habitat's denizens and Turkle (1994) describes how its users actively discussed its morality, "spending their leisure time debating pacifism, the nature of good government, and the relationships between representations and reality" (p165). This behavior, whereby users actively engage with morals and develop their own sense of morality, exemplifies Schulzke's final argument. The future of VE ethics is in flux, though counterintuitively, it may be true that "to constrain VR [virtual reality] users is to deny them the chance to be moral" (Whitby, 1993, p10).

Appendix F: Simulator Sickness Symptomology

1. Introduction

Simulator sickness is a well-known and longstanding issue for VE users (e.g., Kennedy & Frank, 1985), and unfortunately, a large proportion of today's users still experience simulator sickness (Norman, 2018; Yildirim, 2019). Researchers have organized simulator sickness symptoms into different categories (e.g., Kennedy & Frank, 1985; Kennedy et al., 1993; Nichols et al., 1997) and use various terminologies (e.g., Howarth & Costello, 1997; Sharples et al., 2007; Stanney et al., 1999). In this review, I exclusively use the term simulator sickness and I delineate three categories of symptomology (visual, nauseogenic, and behavioral) based on Kennedy et al.'s (1993) Simulator Sickness Questionnaire.

2. Visual Symptoms

Visual symptoms of simulator sickness are those that affect the visual system, including blurred sight, double vision, sore eyes, ocular pressure, and fixation difficulty (Lambooij et al., 2007). These visual symptoms can onset rapidly, occurring within ten minutes of VE exposure (Rushton & Riddell, 1999) and certain effects (e.g., impaired hand-eye coordination) can be particularly long lasting (Stanney et al., 1999).

Visual symptoms occur primarily in HMDs (Sharples et al., 2007) due to an inaccurate replication of binocular depth cues in the stereoscopic visual display (Hettinger et al., 1987). As Geng (2013) states, a conflict of depth cues known as the accommodation-convergence breakdown is the likeliest cause of visual symptoms in stereoscopic displays. During natural stereopsis, the eyes converge (i.e., rotate inward or outward) and accommodate (i.e., focus the lens) to a single point of fixation in synchrony. However, the user has contradicting fixation points in a stereoscopic display, in that the eyes converge to the distance of a virtual object but accommodate to the distance of the display lens (Lambooij et al., 2007). Thus, the accommodation and convergence cues are often asynchronous in a HMD and the visual system strains while attempting to reconcile the discrepancy (resulting in eye ache, visual strain, double vision, etc.) (Geng, 2013; Lambooij et al., 2007). The accommodation-convergence breakdown is unique to stereoscopic displays, and researchers report low visual symptom prevalence in users using monoscopic displays (Rushton et al., 1994; Sharples et al., 2007).

Accounting for individual differences in inter-pupillary distance (IPD), which determines the degree to which the eyes converge to a fixation point, can reduce the effect of an accommodation-convergence breakdown (Lambooij et al., 2007); adult IPD is 63 millimeters on average (Howarth, 1999) but ranges between 50 millimeters and 70 millimeters (Lambooij et al., 2007). Modern commercial HMDs often allow the user to adjust the inter-screen distance (e.g., HTC Corporation, 2016) and so the inter-screen distance should be set to match the user's IPD prior to use, especially in the cases of extended VE exposures.

3. Nauseogenic Symptoms

Nauseogenic symptoms of simulator sickness include user sweating, paling, salivating, nausea, and emesis (Kingdon et al., 2001; Strauss, 1998). Like visual symptoms, nauseogenic symptoms can have a rapid onset, occurring within exposure times as brief as 15 minutes (DiZio & Lackner, 1997).

Of the above symptom range, user nausea is the most common. Howarth and Costello (1997) report that up to 45% of HMD users experience some level of nausea during exposure. Further, the onset of user nausea can be severe, as researchers report that up to 2% of users in a sample can have an emetic response during the VE exposure (Kingdon et al., 2001; Stanney et al., 2003). The severity of nauseogenic symptoms is especially problematic from the experimenter's perspective, given that nausea is a primary cause of participant drop-out: Balk et al. (2013) report a 14% drop-out rate (averaged across nine prior studies); Stanney et al. (2003) report a 13% participant drop-out rate; Sharples et al. (2007) report a 16% drop-out rate; Howarth and Costello (1997) report a 20% drop-out rate. Each of these researchers noted that simulator sickness, and particularly user nausea, was the primary factor in participant drop-out (Balk et al., 2013; Howarth & Costello, 1997; Sharples et al., 2007; Stanney et al., 2003).

Fortunately, we know the source of simulator sickness nausea, and researchers are confident that end-to-end latency in head-tracking is the primary causal factor (Howarth & Finch, 1999; Meehan et al., 2003). End-to-end latency is a lag time resulting from computer processing, which the HMD user experiences as the visual scene updating after initiated head movement (Mine, 1993). The lag-time between user head movement and the visual display update causes a sensory conflict between the visual system and the vestibular system

(Howarth & Costello, 1997; Knerr et al., 1998; Stanney et al., 2003). Specifically, this visual-vestibular conflict triggers nausea, an automatic bodily defense to induce vomiting and rid the body of apparent toxins (Stanney et al., 2003). The nauseogenic defense response is a vital survival mechanism, though it can be erroneously activated during motion (e.g., as with sea-sickness) and can similarly result from latency in head-tracking (Knerr et al., 1998). Confirming the effect of the visual-vestibular conflict, researchers have repeatedly demonstrated that systems which use head-tracking (e.g., HMDs) induce significantly more nausea than those that do not (e.g., monitor-based displays) (Banos et al., 2004; DiZio & Lackner, 1997; Howarth & Costello, 1997; Sharples et al., 2007).

While end-to-end latency is the evident cause of nauseogenic symptoms, the duration of system latency corresponds with its effect on the user. For example, though one can reliably detect latencies of 33 milliseconds (Ellis et al., 1999), users tend to experience nausea once the latency surpasses 100 milliseconds (Nichols, 1999; Wilson, 1996). Each of these latency thresholds (33 milliseconds and 100 milliseconds) are short temporal durations and an ideal virtual system would therefore be one with near-zero latency. Though a near-zero latency system would eliminate the cause of user nausea, it is an unrealistic option for many HMD users given the still nascent state of the technology. Instead, the latency times reported in the literature tend to vary widely, with experimental studies reporting latencies as low as 16 milliseconds (Ellis et al., 1999) and as high as 550 milliseconds (Howarth & Finch, 1999).

Until technological advancements mitigate the issue of latency, researchers should carefully select their VE content to avoid exacerbating simulator sickness. Careful experimental design can mitigate simulator sickness, and as Balk et al. (2013) report, simulator sickness prevalence varies widely across studies. Balk et al. report a 14% drop-out rate on average across nine studies, however, the study drop-out rate ranged from 0% to 72% with a 21% standard deviation.

4. Behavioral Symptoms

Behavioral symptoms of simulator sickness include user behavioral transfer (Strauss, 1998), addiction (Wilson, 1996), dissociation (Ichimura et al., 2001), bodily neglect (Spiegel, 2018), and physical injury (Lemley & Volokh, 2018). While user addiction and dissociation are arguably psychological phenomenon, I categorize them as behavioral symptoms given their influence on user behavior, as I explain below.

One disconcerting behavioral symptom following user VE exposure is the transmission of virtual behavior to real world action. As I discuss above (Appendix E), Anderson et al. (2010) report that user VE behavior transfers to the real world, and criticism of such research notwithstanding (e.g., Ferguson, 2007), the effect of antisocial behavioral transfer has substantial empirical support (Anderson et al., 2010; Calvert & Tan, 1994; Dill & Dill, 1998; Nowak et al., 2008; etc.). The effect of VE behavioral transfer, more generally, is clearly observable elsewhere, given the evidence for prosocial VE behavioral transfer (Gentile et al., 2009; Greitemeyer & Osswald, 2010; Rosenberg et al., 2013) and the research on various VE applications which explicitly depend on VE behavioral transfer, such as VRET (e.g., Parsons & Rizzo, 2008) and VE-based training (e.g., Seymour et al., 2002). One can safely conclude that VE exposure can affect the user's real world behavior, in ways that can be both beneficial and harmful.

Another disconcerting behavioral change following VE exposure is user addiction. For example, Whitby (1993) warns that the limitless potential of VEs could make them the "ultimate opiate" (p8). The effect of media addiction can be profound, whereby a user neglects them self or their dependents, which in extreme cases has resulted in injury and death (e.g., Spiegel, 2018). Though to my knowledge there is no empirical evidence specifically on immersive VE addiction, recent reviews of related literature suggest that a proportion of videogame users (1.7% to 34% depending on study) meet criteria for addiction (Griffiths et al., 2012) as do some smartphone users (3.1% to 62% depending on study) (De-Sola Gutierrez et al., 2016) and some internet users (0.8% to 26.7% depending on study) (Kuss et al., 2014). These related trends, though the prevalence rates differ widely depending on assessment tool and participant sample, nonetheless suggest that there is an addictive potential for immersive VE technology.

The question of user dissociation, like user addition, is a concern with empirical evidence only recently emerging (Van Heugten-Van der Kloet et al., 2018). The limited evidence to date, however, does suggest that immersive VE exposure can induce acute dissociative experiences in otherwise healthy users (Van Heugten-Van der Kloet et al., 2018) and that the degree of dissociation correlates with the strength of virtual presence during the exposure (Aardema et al., 2010). While dissociation is primarily a psychological phenomenon, it can have profound effects on user behavior (e.g., Ichimura et al., 2001). An example of user behavioral change due to VE dissociation is Chronic Alternate-World Disorder (CAWD), in which the user can no longer distinguish between the real and virtual world (Ichimura et al., 2001). Though rare to date, Ichimura et al. report a case study in which a CAWD sufferer hijacked a plane (carrying over 500 passengers) and fatally stabbed its pilot (Ichimura et al., 2001). Similarly, Timmins and Lombard (2005) and Gumbel (2011) note the occurrences of “Matrix murders,” in which the accused argue that they exist in a simulation, and therefore, the victims are not truly deceased. Though user dissociations of this magnitude are uncommon, Ichimura et al. (2001) warn that the prevalence of VE induced user dissociation is liable to increase as the technology advances.

The final behavioral symptom I discuss is bodily injury. Visual occlusion is an obvious safety concern in HMDs, which fully immerse the user’s vision, and it has resulted in serious injury and fatality among HMD users (Paton, 2017). However, occlusion is also a major factor in the physical safety of augmented reality users (Lemley & Volokh, 2018). Augmented reality is a form of VE in which the user views virtual objects, overlaid onto the real world in real time, with the aid of a display device (Azuma et al., 2001). While augmented reality environments do not fully occlude user vision, they draw user attention from the user’s physical environment, which can have serious costs (Faccio & McConnell, 2018). For example, Pokemon Go, a popular augmented reality environment available on smartphones, contributed to 145,000 motor vehicle accidents, 29,000 bodily injuries, 250 user fatalities, and $7.3 billion in associated costs within the first six months of its release alone (Faccio & McConnell, 2018). While we know little about the behavioral effects of VEs to date, they remain an important and costly risk factor to consider.

Appendix G: Why Virtual Presence Occurs

1. Introduction

In the literature, several high-level explanations attempt to explain why virtual presence occurs at all. I review three of the most common explanations below, per my own review of the literature.

2. An Attentional Perspective

Researchers uniformly agree that attention is an important factor of virtual presence (Coelho et al., 2006; Schubert et al., 1999a; Waterworth &Waterworth, 2003; etc.). The importance of attention on virtual presence makes logical sense: if one does not attend to a stimulus they would not perceive it, and therefore, it would be effectively nonexistent (see Simons & Chabris, 1999). However, proponents of attentional models view attentional allocation not just as a factor, but as the primary cause of virtual presence (Bystrom et al., 1999).

Bystrom et al. (1999), who developed the Immersion, Presence, Performance (IPP) Model, place a primacy on user attention. Bystrom et al. suggest that virtual presence occurs when the user experiences an immersive display with a high fidelity sensory scene, but only if the user “allocates sufficient attentional resources to the virtual environment” (p243). Bystrom et al. additionally argue that including an attention-demanding VE task would inherently strengthen the user’s experience of virtual presence.

Draper et al. (1998) outline a similar but distinct attentional model of virtual presence. In short, the authors suggest that virtual presence depends on the “ratio of [attentional] resources devoted to the computer-mediated environment to total resources available” (Draper et al., 1998, p367). As such, Draper et al. suggest that sensory distraction degrades user virtual presence, as it lowers user attentional allocation to the VE. As in the IPP Model of Presence (Bystrom et al., 1999), Draper et al. state the importance of sensory immersion for virtual presence, emphasizing that an immersive display “restricts allocation of attentional resources” to the VE (1998, p368). Though in contrast to the IPP Model (Bystrom et al., 1999), Draper et al. argue that the ratio (and not the sum) of user attentional resources is the determining threshold for achieving virtual presence.

The attentional models of virtual presence are effective in their simplicity: immersion restricts user attention to the VE display, a high-fidelity scene enhances believability (or simply restricts visual focus), and user attentional allocation compels virtual presence. Empirical evidence also lends support to such attentional models of virtual presence as researchers widely report that attention allocation is an important determinant of virtual presence (Coelho et al., 2006; Schubert et al., 1999; Waterworth & Waterworth, 2003; etc.). Further, attentional models are consistent with related hypotheses on virtual presence. For example, Slater et al.'s (2003) Break-in-Presence hypothesis suggests that virtual presence precipitously breaks when user attention shifts from the virtual sensory stream to that of the physical environment; Bystrom et al. (1999) and Draper et al. (1998) would certainly arrive at a similar conclusion.

However, one can find obvious limitations in current attentional models (e.g., Bystrom et al., 1999; Draper et al., 1998). Both of attentional models, for example, place an emphasis on sensory immersion, which fails to explain how one can feel a compelling sense of presence interacting with non-immersive or low fidelity media (Schubert & Crusius, 2002; Towell & Towell, 1997). Further, researchers have demonstrated that increased user attention to the VE sensory stream does not always enhance virtual presence as the attentional models suggest (e.g., see Mori, 1970). Mori's Uncanny Valley effect describes how user attention, when focused on small defects or abnormalities in the VE, can disrupt the user's experience of virtual presence. While the attentional perspective has merit, its proponents thus far have failed to address contrary findings in the literature, such as the "book problem" (Schubert & Crusius, 2002) or the Uncanny Valley effect (Mori, 1970)

3. An Embodied Perspective

Proponents of an embodied perspective argue that virtual presence develops from the user's mental representation of bodily actions in the VE (Schubert et al., 1999; Schubert et al. 2000). For example, Reiner (2004) suggests that virtual presence occurs when "the perceived sensory patterns [during action in a VE] match memorized sensory cues [of the equivalent real world action] and thus convey a meaning" (p.395). In other words, a high equivalence between the sensory experience of a virtual action (e.g., picking up a virtual baseball) and one's sensory memory of the same physical action (e.g., picking up a real baseball) should elicit a strong sense of virtual presence (Reiner, 2004; Schubert et al., 1999). Reiner refers to this sensory equivalence as resonance; Shubert, Friedmann and

Regenbrecht define the same phenomenon as the meshed pattern of action, referring to the comparison (meshing) of VE sensory actions and real world sensory memories.

The concept of resonance as an explanation of virtual presence elicits interesting implications for our experience of reality in the physical environment. For example, if one caught a gelatinous baseball they would experience a sensory pattern (an amorphous object) inconsistent with their prior sensory memory of baseballs (a solid object), which would be strikingly low resonance. Another interesting hypothetical is the effect on reality judgment if resonance were to unexpectedly break in the real world, for example, if a solid baseball suddenly turned gelatinous. According to the embodied perspective, the sudden break in resonance would substantially lower one's sense of presence in the physical world; though interesting to consider, an experiment to empirically test the effect of breaking resonance in the real world is obviously unfeasible.

Offering another embodied model of virtual presence, Haans and Ijsselsteijn (2012) posit that the human mind incorporates a virtual body into one's own body schema, inducing user virtual presence (Haans & Ijsselsteijn, 2012). This explanation is reminiscent of the Rubber Hand Illusion, in which participants adopt an artificial limb into their own body schema (Botvinick & Cohen, 1998); this phenomenon results from a process of intermodal sensory matching (Botvinick & Cohen, 1998; Ehrsson, 2007; Petkova & Ehrsson, 2008). When the user dons a HMD, they occupy a virtual body in the first-person perspective and receive cues of an intermodal sensory match (e.g., head-motion matches visual-scene motion). According to Haans and Ijsselsteijn, this intermodal matching in the HMD induces the user to adopt the virtual body into their own body schema, similar to a Rubber Hand Illusion, and the user experiences a sense of virtual presence as a result.

4. An Evolutionary Perspective

According to researchers advancing the evolutionary perspective of virtual presence, the brain has not evolved to distinguish increasingly realistic VEs from real world experiences, and as such, VEs can induce a compelling sense of reality (Ijsselsteijn, 2002; Lee, 2004; Riva et al., 2004).

Supporters of evolutionary models argue that presence, our experience of reality, is an evolved mechanism important for human survival (Ijsselsteijn, 2002; Riva & Waterworth, 2003; Waterworth & Waterworth, 2003). For example, Riva et al. (2004)

suggest that presence evolved to allow humans to reliably distinguish external stimuli from internal processes (e.g., daydreams or memories). The importance of this distinction for human survival is abundantly clear, given that, for example, confusing a real lion with the memory of a lion would be a fatal error (Ijsselsteijn, 2002). Further, in our evolutionary history, there was a survival advantage for the human to default an ambiguous sensory experience as real (Ijsselsteijn, 2002). As Ijsselsteijn explains, to our ancestors "what looked like a lion, actually was a lion... and if contemplating the nature of reality at that point would have been a priority, one would have made for an easy lion's snack" (p255). The point being that there is an advantage, which we have inherited through evolution, to bias ambiguous sensory experiences as real. Such a bias would explain why comparatively low-fidelity media can elicit a strong sense of presence, for example, it would explain the reports of early film goers who ran in fear from the depiction of an oncoming train (Coelho et al., 2006; Ijsselsteijn, 2002; Lombard et al., 2000). Ijsselsteijn suggests that this same sensory bias remains and we learn to suppress it, for example, a parent telling a child "it's just a movie," is an instruction to inhibit an evolved mechanism which defaults to treat the movie as real. Though, as technology allows for increasingly realistic virtual experiences, the user will find it increasingly difficult to distinguish between the real and the virtual world.

Appendix H: Factors of Virtual Presence (Extended Review)

1. Visual Immersion

Visual immersion is the degree to which the VE display occludes the user's vision of the physical world. Draper et al. (1998) regard visual immersion as a primary determinant of virtual presence and other researchers provide empirical support for the same, each demonstrating that a fully immersive display causes higher virtual presence than a non-immersive display (Axelsson et al., 2001; Bowman & McMahon, 2007; Gorini et al., 2011).

The effect of an immersive display on virtual presence is partly due to the occlusion of the physical environment, which limits the possibility of a break-in-presence (Slater et al. 2003). Slater et al. state that a break-in-presence occurs when the user responds to real world sensory information instead of the VE sensory information, disrupting the user's experience of virtual presence. Given that non-immersive displays do not fully occlude the physical environment, the user simultaneously receives competing real world sensory information; user of a non-immersive display experiences an effectively constant break-in-presence (see Wang et al., 2006).

Beyond occluding real-world sensory information, immersive displays afford the user an egocentric perspective in the VE (Coelho et al., 2006). Ellis (1991) defines an egocentric perspective as one "constructed from the viewpoint actually assumed by the user" and an exocentric perspective as one "from a position other than that where the user is represented to be" (p.325). In other words, immersive displays allow the user to experience the visual scene from a first-person rather than a third-person perspective. Our experience of the real-world is always egocentric, and replicating this natural perspective in an immersive display demonstrably enhances user virtual presence (Baumgartner et al., 2008; Slater et al., 1996; Usoh & Slater, 1995).

Therefore, fully immersive displays provide the user a dual benefit by occluding real world sensory cues (limiting the possibility for a break-in-presence) and by providing the user an egocentric perspective (replicating our natural perspective).

2. Display Resolution

Display resolution refers to the level of visual detail (acuity) in the visual display, often defined in terms of pixel count (e.g., a 1080 by 1200 pixel resolution) (Alexander et al., 2005). Higher resolution displays depict the VE in finer detail, providing the user a higher acuity visual scene (Geng, 2013). Resolution is an essential component of the visual display, though as Deering (1992) notes, past VE displays have provided the user a level of acuity “below the threshold of legal blindness” (p195). Display resolution has since improved. As a reference, Chung et al. (1989) used a 220 by 320 pixel resolution HMD per eye while the Vive Pro HMD has a 1440 by 1600 pixel resolution.

Though a higher display resolution provides higher visual detail to the user, the effect of resolution on virtual presence is unclear. The logical assumption is that higher resolution enhances virtual presence, as a fine grain visual display brings the user closer to an indistinguishably real sensory experience (Duh et al., 2002). This assumption has empirical support, for example, Duh et al. found that higher display resolution significantly enhances virtual presence. However, in a similar study, Dinh et al. (1999) report null findings, indicating that display resolution does not affect virtual presence. Lee (2004) offers an explanation supporting the latter’s null finding, arguing that our visual periphery is effectively low resolution, and as a result, “humans usually do not care about image fidelity” (p500). Slater et al. (2009) offer an alternative hypothesis for the null effect, suggesting that higher display resolution enhances virtual presence in general, but it also increases the chance of an Uncanny Valley effect if the user notices environmental defects. As Pausch et al. (1996) acknowledge, “the illusion of [virtual] presence is fragile... [and] inconsistencies can instantly shatter the illusion” (p.202). Slater et al.’s reasoning frames high display resolution with this fragility in mind, arguing that while higher visual acuity is beneficial overall, it could adversely affect virtual presence if the user notices defects in scene details.

To date, the effect of display resolution on virtual presence is uncertain. The available empirical evidence is discrepant and the theoretical explanations for the null findings are inconsistent. A further issue is that the available research on display resolution as a determinant of virtual presence is noticeably old, especially in such a rapidly advancing domain (e.g., Dinh et al., 1999; Duh et al., 2002). This said, as the technology advances and display resolutions begin to exceed our perceptual capacity, the question of display resolution on virtual presence may become a non-issue.

3. Field-Of-View

Field-of-view (FOV) is the range of a visual scene viewable to the user at a given time in the VE display, a value expressed in degrees of visual angle (Barfield et al., 1990).

As a reference, our unmediated FOV is 180˚ horizontal (from the left to right eye peripheries) and 150˚ vertical (limited by the cheeks and eyebrows) (Heilig, 1992; Mazuryk & Gervautz, 1996).

There are two preliminary points regarding the discussion of display FOV. First, authors often define display FOV in terms of its horizontal viewing angle only (without vertical angle), a convention seen in the earliest papers on HMDs (e.g., Sutherland, 1968) and publications since (e.g., Czerwinski et al., 2002; Hettinger et al., 1987). I maintain this convention and discuss display FOV in terms of horizontal viewing angle. Additionally, I discuss FOV specifically regarding HMDs, since the FOV of a non-immersive display (e.g., a desktop) is dependent on the user's viewing distance.

Display FOV is an important consideration in VE navigation (Czerwinski et al., 2002), distance perception (Kline & Witmer, 1996), simulator sickness (Hettinger et al., 1987), and virtual presence (Duh et al., 2002). Regarding the latter, researchers have found that maintaining a sufficiently large display FOV, one similar to that of our unmediated visual field, enhances user virtual presence (Duh et al., 2002; Lin et al., 2002). Neale (1997) suggests that a large display FOV affords a greater sense of spatial orientation, which may aid the user in developing a sense of visiting a virtual place (i.e., experience spatial presence), rather than viewing an image.

Portraying a naturally large FOV is an important aspect of creating a realistic visual scene, however, it is one that places a heavy computational demand on computing systems (Geng, 2013). In particular, display FOV and display resolution tend to be inversely related, given the cost of producing a wide-view display with a high pixel density (Zhang, 2007). The technological trade-off between FOV and resolution is likely why past displays afforded users unnaturally limited FOVs, such as the 40˚ FOV in the Sword of Damocles HMD (Sutherland, 1968). Modern commercial systems provide the user with both a comparatively realistic FOV and relatively high resolution. For example, the HTC Vive Pro HMD offers an 110˚ FOV and a resolution of 1440 by 1600 pixels per eye. Modern HMDs, which afford a larger FOV with limited cost in resolution, should theoretically increase virtual presence.

4. Frame Update Rate

The perception of a seamlessly moving visual scene in a VE display is the result of static images, which, when successively presented at high speeds, generates the illusion of apparent motion (Chung et al., 1989). The rapid update of static image frames to create an illusion of motion is a common media tool, observable in comic flip-books, television, and film. The most important aspect in maintaining the illusion of apparent motion is frame update rate, the frequency in which the static image frame refreshes with its successive image (Nichols, 1999; Ramachandran & Anstis, 1986).

In general, VE displays require a frame update rate of at least 25 to 30 frames-per-second (FPS) to induce the illusion of apparent motion (Barfield et al., 1998; Usoh & Slater, 1995; Salisbury & Srinisvasan, 1997). Frame update rates below this threshold present the user with the perception of a "choppy" scene motion rather than a naturally smooth-moving environment. Given the effect of frame update rate on creating apparent motion, Usoh and Slater regard frame update rate as one of the most important factors in a VE display.

The perception of apparent motion is likewise essential for the user to maintain the experience of virtual presence (Barfield et al., 1998). Meehan et al. (2002) empirically demonstrate the same, reporting that a frame update rate falling below 30 frames-per-second diminishes user virtual presence. The effect on user virtual presence of increasing the frame update rates substantially higher than this threshold (e.g., 60 or 90 FPS) is unknown.

5. Perception of Depth

Researchers generally agree that an accurate portrayal of depth cues in a VE is an important factor of virtual presence (Bystrom et al., 1999; Ijsselsteijn et al., 1998). Though there are a range of visual depth cues (Cutting, 1997), the bulk of the research focuses on stereoscopic depth perception in the VE display. The emphasis on stereoscopic depth in VEs makes sense, as researchers argue that stereoscopic depth cues are among the most important in display depth perception (Mikkola et al., 2010; Nawrot, 2003). For example, Mikkola et al. argue that there is a "supremacy of stereopsis over monocular depth cues on portable displays" (p5) while Nawrot suggests that "binocular stereopsis and motion parallax are arguably the most important [depth cues]" (p.841).

As one would expect, the benefit of adding stereoscopic cues to a VE display is demonstrably clear. For example, In the literature on VE task performance, researchers consistently report that stereoscopic displays reduce both user task completion time and task performance error rate (Barfield et al., 1999; Bowman & McMahon, 2007; Ware et al., 1993). The authors of these studies also report large effects, for example, Ware et al. report that participants using a stereoscopic display made approximately one-third the errors of those using a monoscopic display.

In addition to its effect on VE task performance, researchers uniformly report that stereoscopic VE displays enhance virtual presence (Freeman et al., 2000; Ijsselsteijn et al., 2001; Ijsselsteijn et al., 2002; Hendrix & Barfield, 1995; Ling et al., 2014). The importance of stereoscopic depth cues for virtual presence makes intuitive sense, not only are stereoscopic cues powerful indicators of visual depth, but replicating binocular depth more closely emulates our real world visual experience. The user of a monocular display would perceive objects as unnaturally flat, which would noticeably degrade scene realism (Wheatstone, 1838).

This said, binocular depth cues are not always useful. Our binocular depth perception has an effective range of approximately 30 meters (Cutting & Vishton, 1995) and five to ten percent of the population is stereo-blind, unable to use binocular depth cues at any distance (Ijsselsteijn et al., 2005). When we are without binocular depth cues, due to extended range or stereo-blindness, monocular cues become essential to depth perception. Visual scientists have identified a multitude of monocular depth cues, including pictorial cues (e.g., occlusion, linear perspective), size cues (e.g., relative size), and others (e.g., aerial perspective, textural gradient, etc.) (Drascic & Milgram, 1996; Geng, 2013). However, despite their importance in long-range distance perception, there is a void in the research on how manipulating monocular depth cues impacts virtual presence. Prothero et al. (1995) provide some evidence for the impact of monocular depth cues, as they report that manipulating foreground-background cues affects virtual presence. Beyond this single study, however, I am unaware of any research which manipulates monocular depth cues as a predictor of virtual presence. Prior research on monoscopic depth cues tends to focus on VE task performance (Kline & Witmer, 1996) and how depth cue manipulation could mitigate the known compression of distance estimates in VEs (Richardson & Waller, 2007).

6. Auditory Cues

The auditory system, though a lesser focus in the VE literature than its visual counterpart, is nonetheless important in the study of virtual presence. Auditory information in a VE provides additional sensory information, affords sensory cues outside the visual field, and aids spatial orientation, among other advantages (Mazuryk & Gervautz, 1996).

Researchers note the value of adding auditory cues specifically on virtual presence. Viaud-Delmon et al. (2006) report a significant effect of including auditory cues on virtual presence, an effect which others corroborate (e.g., Hendrix & Barfield, 1995). The presence enhancing effect of auditory information is understandable, as the addition of sound cues in a VE should increase the user's sense of sensory realism. Further, as with an immersive visual display, an immersive auditory interface (e.g., over-the-ear headphones) can occlude noise from the physical environment and limit real world sensory distraction.

Several researchers have gone further in their investigation of auditory cues by comparing the effect of binaural versus monaural sound on virtual presence. Hendrix and Barfield (1995), Vastfjall (2003), and Poeschl et al. (2013) each report that the addition of binaural cues enhances virtual presence more than monaural cues. Freeman and Lessiter (2001) investigate the effect of audio quality further by comparing a two-source to a five-source surround-sound system on virtual presence. However, contrary to their expectations, Freeman and Lessiter report no difference between the two-source and five-source audio conditions. The authors presume that the null result was due to their choice of auditory stimuli, an idle-vehicle engine noise, which may lack the sensory nuance necessary to elucidate a meaningful difference between audio-source conditions (Freeman & Lessiter, 2001). An alternative explanation is that audio quality enhances virtual presence to an asymptote, in that the sensory complexity of sound has a diminishing effect on virtual presence (Hendrix & Barfield, 1995). Hendrix and Barfield's hypothesis of an auditory asymptote is comparable to the effect of display resolution on virtual presence, in that, as display resolution begins to exceed human visual acuity the effect of increasing display resolution further would garner a diminishing return.

Despite the research on auditory cues and virtual presence to date, many questions remain. For example, Hendrix and Barfield's (1995) suggestion that audio quality increases virtual presence to an asymptote is an interesting yet untested idea. Additionally, the effect of presenting the user with a visual scene (e.g., a virtual office) and incongruent audio information (e.g., engines running) is unknown. These are just two of many potential follow-up studies which would advance our understanding of virtual presence.

7. Haptic Cues

The haptic system relates to the sense of touch, including our perception of temperature, vibration, pressure, and limb position in space (Haans & Ijsselsteijn, 2006). Researchers regard haptic feedback as an important, if not essential, factor in virtual presence (e.g., Reiner, 2004). Empirical research supports the importance of haptic information on virtual presence, as multiple researchers confirm that the addition of haptic information enhances virtual presence (Dinh et al., 1999; Haans & Ijsselsteijn, 2006; Hoffman et al., 1998; Sallnas, 1999; etc.).

An important aspect of VE haptics, beyond the experience of manual touch, is replicating kinesthesis. Kinesthesis is a haptic-subsystem responsible for the perception of our own limb position in three-dimensional space (e.g., it allows one to touch their nose even with closed eyes) (Haans & Ijsselsteijn, 2006; Reiner, 2004; Srinivasan & Basdogan, 1997). Arguably, the most important aspect of kinesthesis in a VE is the affordance of user head-tracking. The intent of VE head-tracking is to replicate an element of human kinesthesis, whereby the user's self-initiated limb movement (head motion) matches changes in the visual scene, as happens in our real world experience. Head-tracking in is an extremely important feature, which Sutherland (1968) incorporated in the first HMD as do all modern HMD manufacturers (e.g., HTC Corporation, 2016). Brooks (1999) emphasizes the importance of head-tracking, calling error in head-tracking the "greatest illusion breaker" (p18) of virtual presence; other researchers have reinforced this same idea in their own writing (e.g., Hendrix & Barfield, 1995). Meehan et al. (2003) provide further evidence for the importance of head-tracking, as they empirically demonstrate that visual-kinesthetic cue conflict (caused by head-tracking error) is a major detractor of virtual presence. This said, I have not seen a study which investigates the total absence of head-tracking on virtual presence. The absence of this research itself speaks to the universal assumption that head-tracking is a primary component of virtual presence.

8. Gustatory and Olfactory Cues

Following a review of the literature, I know of very few empirical studies which investigate the effect of gustatory or olfactory cues on virtual presence. Hoffman et al. (1998) report that participants experience significantly higher virtual presence with the addition of gustatory and olfactory cues compared to an imagined smell and taste control group; Dinh et al. (1999) find that the addition of olfactory cues in a VE increased participant virtual presence, though this result was not statistically significant. Despite the non-significant result, Dinh et al. rightfully advocate for further research into gustatory and olfactory, given the large gaps in the literature on the topic.

The lack of research in these domains is due in part to technological limitations. Interfaces that replicate taste and smell are nascent, and only recently have modern VE developers began focusing on simulating these cues (e.g., Obrist et al., 2016). The state of the technology is not necessarily for lack of trying; Heilig (1962) invented a VE system which emulated smell cues (the Sensorama) over 50 years ago. As Heilig notes in his paper describing the Sensorama, and as others have noted since, creating synthetic taste and smell cues is extremely difficult (National Security Agency, 2011). The two studies which I describe above (Dinh et al., 1999; Hoffman et al., 1998) exemplify this difficulty, as both groups of researchers rely on physical objects to create “virtual” tastes and smells. Hoffman et al.’s participants ate a real chocolate bar, and Dinh et al.’s “virtual” aroma (a coffee scent) required actual coffee grounds. Using physical objects for taste and smell cues challenges the validity of these results, and in general, it defeats the purpose of studying computer-generated sensory cues on virtual presence.

Though difficult, accurately replicating olfactory and gustatory sensory cues would logically increase virtual presence. Further, the replication of all sensory information (taste and smell included) is necessary to create Sutherland’s (1965) Ultimate Display, or to meet the similarly lofty goals in literature (e.g., see Lauria, 1997; Steuer, 1992).

9. Real World Sensory Distraction

Modern VE systems do not fully immerse the user’s senses, and instead, the user receives competing sensory information from the real world. For example, the user may perceive distractions including background noises, unexpected touches, physical discomfort from the headset fit, and similar distractions (Nichols, 1999).

Researchers repeatedly demonstrate that real world sensory distraction can reduce the user’s sense of virtual presence (Jerome & Jordan, 2007; Nichols, 1999; Van Schaik et al., 2004; Wang et al., 2006; Witmer & Singer, 1998). The degrading effect of sensory distraction is observable in other medias as well, for example, quiet places lend themselves to “getting lost” in a book, while darkened and hushed theaters are clearly meant to immerse the viewer into a film. Given the importance of controlling sensory distraction, it is unsurprising that popular measures of virtual presence (e.g., the PQ) include items specifically to gauge sensory distraction (Witmer & Singer, 1998).

10. Environmental Realism

Sutherland's (1965) seminal work, The Ultimate Display, describes the potential of VEs to create "a looking glass into a mathematical wonderland," allowing users to explore "concepts not realizable in the physical world" (p1). Sutherland is portraying the ability of VEs to manipulate environmental realism. As Lombard et al. (2000) define it, environmental realism is the degree to which the VE "is plausible or 'true to life' in that it reflects events that do or could occur in the nonmediated world" (p2). The notion that a VE can introduce surreal elements is a common theme in the literature (Robinett, 1992; Schroeder, 2002; Wann & Mon-Williams, 1996), however, despite the popularity of the idea, the effect of manipulating environmental realism on the user's experience of virtual presence is an effectively wide-open research direction.

11. Narrative

As Gorini et al. (2011) state, a VE's narrative is the overarching theme "that users can inhabit from a first-person perspective" (p100). Slater and Wilbur (1997) identify the same concept, defining VE narrative as "a story-line that is self-contained, has its own dynamic, and presents an alternate unfolding sequence of events" (p4) to those of the real world. VE narrative includes features such as the explicit storyline (e.g., a written prologue or instructions), the appearance of the scene objects, the emotional tone of accompanying sounds, and the actions or dialogue of computer generated agents.

Narrative is an important factor of virtual presence, and prior to VEs, an important factor in the presence experience of film, literature, and theater (Banos et al., 2005; Green et al., 2004; Schubert & Crusius, 2002). The effect of narrative is likewise observable in modern VEs, and many researchers maintain that narrative is an important factor of virtual presence (Banos et al., 2004; Gorini et al., 2011; Green et al., 2004; Slater & Wilbur, 1997; Towell & Towell, 1997).

An important consideration for VE narrative is the level of emotional content it solicits from the user because, as Pausch et al. (1996) state, those who are emotionally involved with a narrative are more easily convinced by it. Klimmt and Vorderer (2003) identify the same effect, indicating that emotional narratives aid the user in forgetting that the experience is technologically mediated and allows one to fully "melt into" (p348) the VE. However, the tight coupling of VE narrative and user emotion presents a challenge from a research perspective given that it difficult (and perhaps impossible) to parse a narrative from the user's resulting emotion. For example, Gorini et al. (2011) use a VE narrative in which participants search for an anecdote for a poisoned child while avoiding "a mad murderer… trying to kill them" (p100). Gorini et al. conclude that narrative increases virtual presence, but it is impossible to determine whether the storyline or the presumed user emotion (empathy for the child, fear of the murderer, etc.) led to the observed effect. The confound is explicitly clear in the work of Banos et al. (2004) who compare a "sad" and "neutral" narrative on virtual presence. Glicksohn and Avnon (1997) identify this confound in their own work, stating that their choice of a violent VE narrative, which may have affected the participants emotions, could have influenced their results.

The emotion inducing nature of a VE narrative raises additional research questions. Though researchers widely report that VEs can induce user emotion (Alsina-Jurnet et al., 2007; Waterworth et al., 2004), it is unclear if virtual presence causes heightened emotion or if emotion causes heightened virtual presence (Schuemie et al., 2001; Vastfjall, 2003). Complicating the question of causal directionality is Vastfjall's suggestion that presence "is not a separate construct from emotional reaction, but a feeling of presence *is* actually an emotion" (p186, italics added). William James (1890) offers a similar argument, suggesting that "in its inner nature, belief or the sense of reality, is a sort of feeling more allied to the emotions than anything else" (p197). Huang and Alessi (1999a) concur, suggesting that, as virtual presence is viscerally felt, it is the same phenomenal experience as emotion.

Though the empirical evidence remains disputed, it appears that both narrative and user emotion influence the experience of virtual presence. The most immediate challenge for researchers is to carefully parse narrative from user emotion in order to determine their unique contributions on virtual presence. Though alternatively, Alcaniz et al. (2003) argue that narrative and emotion are inextricably bound together, and therefore, researchers may choose to treat the two together as a single factor. This in mind, future researchers have competing directions forward: one can attempt to parse narrative from emotion to study their individual effects or treat narrative and emotion as an inseparable variable.

12. Avatar Appearance

VEs often afford the user a virtual self-representation, an avatar, which represents their body in the virtual world (Fox, Arena, et al., 2009). Avatar appearance can significantly affect virtual presence, as exemplified by the Uncanny Valley effect, which describes how avatar defects can degrade virtual presence (Mori, 1970). Since Mori's original work, other researchers have provided evidence for the Uncanny Valley effect (e.g., Bartneck et al., 2007; Dill et al., 2012; Geller, 2008; Seyama & Nagayama, 2007). Researchers have identified other ways in which the VE avatar affects user virtual presence. For example, Nowak and Biocca (2003) report that avatar anthropomorphism is negatively correlated with virtual presence; however, Parise et al. (1996) report results contrary to this, finding that avatar anthropomorphizing does not impact virtual presence. Without further research, it is difficult to draw concrete conclusions from these limited and conflicting reports, especially as the studies vary across multiple third variables (display type, etc.).

Investigating a similar phenomenon in avatar appearance, Bailenson et al. (2001) found that users apply different interpersonal space norms to their own virtual self (an avatar modeled from their appearance) compared with a virtual stranger (an avatar modeled from a stranger). Interestingly, Bailenson et al. report that users self-report similar levels of virtual presence across these conditions, though they differ in the amount of interpersonal space given to the avatar. In a similar study, Bailey et al. (2009) report that participants who customize their avatar in their own image experience higher virtual presence than those assigned a random appearance; Ratan et al. (2007) garner similar results, finding that users who customize an avatar to resemble their own likeness experience higher virtual presence.

In aggregate, these studies on the Uncanny Valley, avatar anthropomorphizing, contact with a virtual self, and avatar customizability, indicate that a complex (and largely unexplored) set of avatar appearance factors could affect the experience of virtual presence.

13. Social Interaction

Users interaction within a VE is an important factor of virtual presence with a firm basis of evidence in the empirical literature (e.g., Schubert et al., 2000). However, while researchers often note highlight social interaction as a critical factor of a VE (e.g., Heeter, 1992), Biocca (1997) notes that developing social interaction in a VE, from a technological standpoint, is a "horrendously complex" challenge (p18). Several other authors acknowledge the technical difficulty while implementing virtual interactions, noting challenges such as supporting remote users on a shared online server (Benford et al., 2001), programming avatars to depict movement (Whalen et al., 2003), and reflecting VE changes to all users simultaneously (Takemura & Kishino, 1992). Additionally, user interaction in VEs is often unnatural, given that users in past VE systems afford users with a strikingly limited range of actions (Benford et al., 1995; Slater, 1999a).

Despite the technological hurdles, researchers have empirically demonstrated the importance of social interaction on virtual presence. Schubert et al. (2000) report that VE interaction increases user virtual presence; Garau et al. (2005) report that users exposure to responsive avatars (as opposed to static figures) leads to higher virtual presence; Nowak and Biocca (2003) report that users who simply see another avatar experience higher virtual presence than those who do not. The aggregate of these findings suggests that social interaction in a VE does enhance virtual presence.

14. Trait Absorption

Absorption refers to a psychological state of "total attention" in which one has a "heightened sense of the reality of the attentional object" and an "imperviousness to distracting events" (Tellegen & Atkinson, 1974, p268). Banos et al. (1999) provide a slightly different definition of the same underlying concept, defining absorption as "the tendency to become fully involved in a perceptual, imaginative, or ideational experience" (p144). Taking these definitions together, absorption is a feeling of total engagement in a task or experience, which Tellegen and Atkinson emphasize is a disposition (i.e., trait) of the individual.

On the surface, absorption and presence are similar constructs. As Murray et al. (2007) point out, measures used to predict virtual presence (e.g., the Immersive Tendencies Questionnaire) and measures of absorption (e.g., the Tellegen Absorption Scale) have noticeably similar items. However, despite their outward similarities, absorption and presence are separate constructs. A key difference is that absorption is task specific, in other words, absorption occurs specifically when one is fully engaged with a specific task or focal object (Tellegen & Atkinson, 1974). Alternatively, presence is a global sense of reality judgment, independent of a task (or focal object) and occurs independently of total mental engagement. Though trait absorption and presence appear similar at a glance, researchers rightfully treat them as distinct variables (e.g., Murray et al., 2007).

Past researchers have thoroughly investigated trait absorption, an individual's disposition to become absorbed, as a predictor of virtual presence (Banos et al., 1999; Murray et al., 2007; Kober & Neuper, 2013; Sas, 2004; Sas & O'Hare, 2003a). Unfortunately, the findings on trait absorption as a predictor of virtual presence are discrepant. While much of the research concludes that trait absorption and virtual presence are positively correlated (Banos et al., 1999; Kober & Neuper, 2013; Sas, 2004; Sas & O'Hare, 2003a), recent research suggests that no correlation exists (Murray et al., 2007).

Unfortunately, it is difficult to compare experimental results on trait absorption due to fundamental methodological differences across the studies. One difference is that researchers use different measures of virtual presence (e.g., see Banos et al., 1999; Murray et al., 2007; Kober & Neuper, 2013; Sas, 2004; Sas & O'Hare, 2003a). The differences in measurement makes it difficult for one to determine which study, if any, accurately measured the primary dependent variable. Murray et al. state the same, arguing that their (null) finding is accurate given that they "used a more robust measure of presence than that employed in the study by Banos et al" (p1352). Murray et al.'s null result is also in stark contrast with Kober and Neuper, who conclude that, of the seven predictors measured, "absorption seems to be the best predictor for presence" (p21). Given the difference in their measures, it is currently difficult (or impossible) to determine the true effect (if any) of trait absorption on presence.

The differences across experimental procedures is another potential cause of the discrepant results. For example, Murray et al. (2007), who report a null result, simply had participants explore a virtual cityscape to find a statue. In contrast, Sas and O'Hare (2003a), who report a significant result, employed a much more active narrative in which participants searched a virtual art museum to catch a thief. Differences in their results is likely due, in part, to these procedural differences and the influence of various other third variables (task, narrative, display, etc.).

15. Dissociative Tendency

Aardema et al. (2010) define dissociation as a "sense of detachment and unreality toward oneself or the external [real] world" (p429). The symptoms of dissociation range from normal daily processes (e.g., daydreaming) to chronic breaks with reality (Aardema et al., 2010). In the literature, researchers regard dissociation as a psychological trait, whereby individuals vary in their tendency to have dissociative experiences (Banos et al., 1999; Wallach et al., 2010).

The effect of user dissociative tendency on virtual presence is unclear. Researchers have reported both a positive correlation between dissociative tendency and virtual presence (Banos et al., 1999; Murray et al., 2007) and no correlation (Wallach et al., 2010). As with the research on trait absorption, it is difficult to compare experimental results across past studies. First, the researchers investigating dissociative tendency as a factor of virtual presence employ different presence measures (e.g., see Banos et al., 1999; Murray et al., 2007; Wallach et al., 2010). Second, dissociative tendency is a non-manipulable predictor, so researchers cannot determine causality; even those researchers reporting a significant correlation between dissociative tendency and virtual presence face the limitations of non-experimental designs (i.e., the third variable and causal directionality problems).

16. Immersive Tendency

Witmer and Singer (1998) conceptualize immersive tendency as the user's capacity to experience presence in an unreal world (a daydream, a VE, etc.), for example, their Immersive Tendencies Questionnaire (ITQ) includes items such as "do you ever have dreams that are so real that you feel disoriented when you awake?" (p234). This said, immersive tendency and trait absorption are observably similar constructs, and while they appear similar, an important difference is their respective focuses. Trait absorption is task specific, and the Tellegen Absorption Scale (Tellegen & Atkinson, 1974) includes task-specific items (e.g., "I like to watch cloud shapes change in the sky"); immersive tendency is presence specific, and the ITQ (Witmer & Singer, 1998) includes questions presence-specific items (e.g., "Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?"). Though trait absorption and immersive tendency tend to correlate ($r = .31$), researchers maintain that they are distinct variables (Murray et al., 2007).

In theory, an individual with higher immersive tendency would be more likely to experience virtual presence. However, as with the other psychological factors that I discuss, there are discrepancies across empirical results. Some researchers to date report that immersive tendency and virtual presence are positively correlated (Kober & Neuper, 2013; Wallach et al., 2010; Witmer & Singer, 1998) while others report no correlation (Aardema et al., 2010; Murray et al., 2007). There is an additional discrepancy among those who found significant correlations, given that, depending on the study, the correlation coefficients range from moderately weak (r = .29) to very strong (r = .86) (Wallach et al., 2010 and Johns et al., 2000 respectively).

An explanation for the conflicting results is poor measurement validity, in this case the validity of the ITQ is questionable. Witmer and Singer's (1998) ITQ is an extremely common measure of immersive tendency (e.g., Aardema et al., 2010; Murray et al., 2007; Kober & Neuper, 2013), and though it is reliable (α = .75) there is little evidence for its predictive validity. Witmer and Singer (1998) identify its questionable validity in their own development of the ITQ, acknowledging that "only two of the four experiments resulted in a significant correlation between ITQ and PQ [virtual presence] scores" (p237). Given this, it is unclear whether the ITQ is a valid measure of immersive tendency, or alternatively, if the PQ is an invalid measure of virtual presence.

Further complicating the interpretation of immersive tendency as a predictor of virtual presence is the reoccurring issue of virtual presence measure validity. Kober and Neuper (2013) compared the correlation between immersive tendency, using the ITQ, and virtual presence, using four different virtual presence measures. Kober and Neuper report that immersive tendency and virtual presence correlate, though the strength of the correlation depends on the presence measure (r = 0.25, r = .036, r = .44, and r = 0.47). As Kober and Neuper summarize, immersive tendency showed "heterogeneous correlations with [virtual] presence, depending on the presence questionnaire used" (p23).

To advance our understanding of immersive tendency as a factor of presence, future researchers should validate the ITQ and validate the common measures of virtual presence, and if need be, develop valid alternative measures.

17. Locus of Control

Locus of control is the degree to which one attributes events as having external or internal causes (Rotter, 1966). Those with an external locus tend to attribute events (e.g., a job promotion) to factors outside of their own control (e.g., luck), while those with an internal locus tend to attribute events to their own actions (e.g., work ethic) (Rotter, 1966).

Researchers identify locus of control as a predictor of virtual presence, specifically, many in the field hypothesize that users with an external locus of control will experience higher virtual presence (Kober & Neuper, 2013; Murray et al., 2007; Wallach et al., 2010). As Wallach et al. hypothesize, those with an external locus of control feel a lack of causal agency over life events and therefore should be more easily influenced by the VE, experiencing higher virtual presence as a result.

Empirical research supports the idea that locus of control affects one's sense of reality judgment. For example, Murray et al. (2007) report a significant correlation between locus of control and the tendency to have dissociative experiences. Further, Rickenberg and Reeves (2000) report that external locus individuals are more influenced by external stimuli, which may predict a stronger sense of presence in a VE. However, the evidence for a relationship between locus of control and virtual presence is inconclusive. Murray et al. report a significant correlation ($r = 0.22$) between external locus and virtual presence; Wallach et al. (2010) found no significant correlation, but their results trend toward an internal locus and virtual presence correlation; Kober and Neuper (2013) report a null result between locus of control and virtual presence with no obvious directional trend.

There are several explanations for the contradictory results. First, the explanation that different measures are leading to different results is once again valid here. Wallach et al. (2010) suggest the same, arguing that other studies (e.g., Murray et al., 2007) use invalid virtual presence measures. Second, different VE displays and differing content across experiments may be influencing results. For example, Murray et al. used a HMD with a navigable VE, while Wallach et al. used a HMD with non-navigable VE, and Kober and Neuper (2013) used a non-immersive display with a navigable VE. The difference between these experimental designs (level of immersion, navigability, etc.) introduces several uncontrolled variables, any of which could explain the inconsistent results. Given that none of the above researchers employed a factorial design, there is no evidence on the potential interaction of these extraneous variables.

18. Personality

According to the American Psychological Association (2018), personality is a combination of multiple individual traits which define one's thoughts, emotions, and behaviors. Personality is a complex construct, and the American Psychological Association notes that personality researchers investigate both individual personality traits (e.g., extraversion) and the combination of these traits which form one's global sense of self. The research on personality and virtual presence tends to follow the former approach, by measuring single personality traits as predictors.

An initial point for discussion is the effect of the Myers-Briggs Type Indicator (MBTI) personality traits (Myers, 1962). The MBTI is a well-known measure which defines traits along four scales: extraversion-introversion, sensing-intuition, thinking-feeling, and judging-perceiving (Myers, 1962; Briggs, 1976). Researchers using the MBTI report that three of these traits significantly affect virtual presence, whereas introverted (I), sensing (S), and feeling (F) individuals tend to experience higher virtual presence (Sas, 2004; Sas et al., 2004). In other words, users who prefer solitary activity (introversion), rely on their senses (sensing), and follow their emotion (feeling), as defined by the MBTI (Briggs, 1976), experience higher virtual presence. According to Sas and O'Hare (2003), no significant effect emerges from the judging-perceiving dimension of the MBTI trait scale.

Though the MBTI is an exceptionally well-known personality scale, many other measures of personality exist. In the virtual presence literature alone researchers use an immense range of personality measures, including the Eysenck Personality Questionnaire (EPQ), Zuckerman-Kuhlman Personality Questionnaire (ZKPQ), Barratt Impulsiveness Scale (BIS), NEO Personality Inventory (NEO-FFI), Interpersonal Reactivity Index (IRI), Saarbrucken Personality Questionnaire (SPF) and others (Kober & Neuper, 2013; Laarni et al., 2004; Sacau et al., 2005; Wallach et al., 2010). Given the vast range of personality measures in the literature, I focus the following discussion on results, rather than describing each measure in detail (as I do with the MBTI above).

Several other personality traits appear to influence virtual presence. Laarni, et al. (2004) report that individuals who are impulsive, extraverted, and lack strong sense of self identity, tend to experience higher virtual presence; their finding that extraversion correlates with virtual presence contradicts Sas' (2004) finding that trait introversion correlates with virtual presence. Researchers have additionally found that trait empathy (Sas, 2004; Wallach et al., 2010), activity of imagination (Sas, 2004; Wallach et al., 2010), and agreeableness (Sacau et al., 2005) correlate with higher levels of user virtual presence.

The research on personality and virtual presence gains additional complexity given the dynamic nature of one's personality paired with the numerous personality measures available. For example, both introversion (Sas, 2004; Sas et al., 2004) and extraversion

(Laarni et al., 2004) show significant correlations with virtual presence, perhaps because the researchers used different measures of introversion-extraversion (the MBTI and Eysenck Personality Questionnaire, respectively). These contradictory results do not necessarily indicate one finding is void, but rather, could indicate that one of the measures for introversion-extraversion may be gauging another construct than intended. Similarly, considering the fluctuating nature of personality, a measure could be gauging a participant personality state (e.g., feeling extroverted that day) rather than personality trait (e.g., extroversion as a personality characteristic). Further, researchers have not yet replicated many studies of the studies on personality and virtual presence, and as such, some findings may simply be Type I or Type II errors.

Regardless of the reason, our knowledge on the relationship between personality and virtual presence is based on mixed empirical evidence. Though the impact of personality is not conclusively understood, some virtual presence researchers place a special emphasis on personality. For example, Sas and O'Hare (2003) suggest that personality provides "a distinct *flavour* to [one's] sense of presence" (p4, italics in original) while Tart (1986) suggests that personality is "largely synonymous" (p163) with consciousness. Though these authors do not explain their ideas in detail, the notion that personality may tint (or determine) our experience of reality is an interesting notion worth some consideration.

19. Mental Model Construction

In this context, a mental model is an internal representation, a cognitive spatial model (or mental map), which one gains of an environment (Schubert et al., 2001). Schubert et al. use the example of reading a description of a narrow suspension bridge built across a gorge, whereby the written description alone affords the reader an imagined view of the scene. According to Banos et al. (2005), in the context of a VE, the visual scene acts as the "raw material" in which we build "a mental model of the space around the body" (p91).

Despite some ambiguity in the literature on how the brain constructs a mental model, the ability to gain this representation is generally thought to be an important component of virtual presence (Sacau et al., 2005; Slater, Usoh & Steed, 1995; Schubert & Crusius, 2002; Van Schaik et al., 2004). Researchers consider mental model construction an ability of the user, subject to individual differences in cognitive ability (Howe & Sharkey, 1998; Sacau et al., 2005). This notion has empirical support, as Alsina-Jurnet and Gutierrez-Maldonado

(2010) report that users with higher spatial intelligence more readily construct mental models and these users also experience higher virtual presence. Adding support specifically for spatial intelligence as a factor of mental model construction, Alsina-Jurnet and Gutierrez-Maldonado report that there is no correlation between user verbal intelligence and virtual presence. The authors conclude that spatial intelligence aids “the active construction of a mental model of the virtual space” (p791) and therefore enhances virtual presence (Alsina-Jurnet & Gutierrez-Maldonado, 2010). Though the empirical research to date is sparse, the available evidence to date generally supports the idea that mental model construction is a factor in experiencing virtual presence.

20. Attention Allocation

Attention allocation refers to the user’s ability to devote attentional resources to the VE while suppressing sensory information from the physical environment (Schubert et al., 2001). As with mental model construction, researchers regard attention allocation as a cognitive ability subject to individual differences (Schubert et al., 2001). The importance of user attentional allocation on virtual presence is indisputable, to consciously perceive a stimulus one must first attend to it (Simons & Chabris, 1999). As Freeman et al. (2000) state, the “notion of presence is inextricably bound up with attentional factors” (p150).

Using an analogy adapted from Waterworth and Waterworth (2001), one can think of user attention while interacting with a VE as a single lit candle in a two-room apartment: at any one time the candle can illuminate one room (i.e., the VE sensory stream) or the other (i.e., the real world sensory stream), but not both rooms simultaneously. According to Draper et al. (1998), the more attentional resources that the user devotes to the VE, rather than the physical environment, the stronger the virtual presence they experience. To date, no VE system provides absolute sensory immersion (i.e., full immersion of all senses) and sensory cues from the real world compete for limited attentional resources. Therefore, users with a strong ability to allocate their attention to the virtual sensory stream, while suppressing the real world, should experience higher virtual presence. Slater et al.’s (2003) Break-in-Presence hypothesis, which states that real world distraction breaks virtual presence, corroborates the importance of user attentional allocation. Additionally, Hecht and Reiner (2007) report that participants with a higher ability to suppress contradictory sensory cues experience higher virtual presence.

Schubert et al. (1999) argue that one's ability to allocate attention to a media, while suppressing sensory distraction, explains how low-immersion media (e.g., a book) induces a shift in presence (Schubert & Crusius, 2002). Though a book has low sensory fidelity, the ability to focus on the text while suppressing sensory distractors can elicit an experience of presence in the narrative (Schubert & Crusius, 2002). Reading in a quiet place, where sensory distraction is low, serves to enhance the feeling of presence in the literary narrative. Similarly, VE displays that provide more sensory immersion (lowering sensory distraction) induce significantly higher virtual presence (Axelsson et al., 2001; Bowman & McMahon, 2007; Gorini et al., 2011).

Interestingly, immersive VE displays effectively suppress sensory distraction on the user's behalf, which may wash-out the effect of the user's ability to allocate attention and suppress distraction. In other words, there may be an attentional ability and display immersion interaction effect, whereby only users with a strong ability to allocate attention experience presence in a low-immersion media (e.g., a book) and all users experience presence in high immersion media (e.g., a HMD). To date, I know of no prior work which investigates this hypothesis.

21. Demographic Factors

Presence at its core is a psychological experience, however, it is useful to consider how demographic differences affect the phenomenon. The available research to date is primarily focused on two demographic factors: user age and user sex.

User age is a demographic factor of particular interest in the literature. For example, the research comparing children and adults in VEs covers a range of topics, including VE navigation differences (McCreary & Williges, 1998; Volbracht & Domik, 2000), virtual classroom learning (Brelsford, 1993), simulator sickness (Lambooij et al., 2007), and virtual presence (Van Schaik et al., 2004). Regarding the latter, Van Schaik et al. report that there is a strong negative correlation ($r = -0.70$) between age and virtual presence. This said, Van Schaik et al.'s work alone is insufficient to form conclusions, especially as the authors acknowledge that older participants often have less experience with VE controllers (controller experience being a confounding variable). In another study, Baumgartner et al. (2008) compared virtual presence in children and adults with both self-report and neurological (fMRI) measures. Contrary to Van Schaik et al., Baumgartner et al. found that children and adults self-report similar levels of virtual presence, however, adults and children have different brain activation patterns during VE exposure (Baumgartner et al., 2008). In short, Baumgartner et al. state that the differences in brain activation demonstrates that adults can moderate their experience of virtual presence while children (with an undeveloped prefrontal cortex) cannot (Baumgartner et al., 2008). This finding suggests that age does impact virtual presence, in that children cannot moderate or inhibit the experience as can adults; it is unclear, however, why this difference was unobservable on self-report measures of virtual presence.

Beyond age, user sex is the only other demographic variable I have found following a review of the literature. Researchers report that sex influences VE navigation (Czerwinski et al., 2002; Sas, 2004; Woolley et al., 2010), VE task performance (Barfield et al., 1990), simulator sickness (Curry et al., 2020; Munafo et al., 2017; Stanney et al., 1999), and virtual presence (Lachlan & Kremar, 2011). The research to date on sex and virtual presence suggests that men experience higher virtual presence than women (Felnhofer et al., 2012; Lachlan & Kremar, 2011) though this difference may only apply to the spatial dimension of virtual presence (Felnhofer et al., 2014).

22. Cultural Background

The final internal factor of virtual presence is user cultural background. As Lombard and Jones (2015) state, it is "difficult to imagine any presence encounter that is not shaped by language and culture" (p27). Though researchers often discuss culture as an important factor of virtual presence (Banos et al., 2004; Lombard & Jones, 2015; Mantovani & Riva, 1999; Tart, 1986; Villani et al., 2012; etc.), no researcher provides an operationalized definition of "culture" in this context.

In this paper, I assume that past researchers use "culture" to mean one's societal background, including learned social values, religious views, and cultural norms. I use the term "cultural background" here to emphasize that user culture provides a background context to interpret the believability of a VE experience. Mantovani and Riva (1999) and Tart (1986) take a similar view, each suggesting that cultural background informs one's understanding of reality. For example, Tart (1986) notes that some cultures accept dreams as important events which can influence the events of the real world, while other cultures regard dreams as an epiphenomenon of mental processing. Tart (1972) provides another interesting interaction between cultural background and reality judgment, noting that certain groups treat religious experiences (e.g., speaking in tongues or visions) as authentically real experiences, which affects their perception of reality relative to other cultural groups. In this way, cultural background certainly can inform one's understanding of reality.

Unfortunately, I know of no research which empirically investigates cultural background as a predictor of virtual presence, though researchers have noted the effect of user culture as a third variable. For example, Wallach et al. (2010) found that participants who moved their head during VE exposure experienced significantly higher virtual presence, however, 27% of their participants did not move their head to any large degree. Wallach et al. conducted their study in the Middle East and the participants who did not move their head were predominantly Arab-Muslim women. The authors suggest that the difference in cultural background explains the limited head movement which subsequently degraded their sense of virtual presence. This conclusion provides some evidence that cultural background affects virtual presence, albeit in an unanticipated way.

Seyama and Nagayama (2007) provide another case of cultural background affecting virtual presence. Seyama and Nagayama advance that cultural background moderates the Uncanny Valley effect, in that Japanese participants have a higher tolerance for abnormal features (e.g., unusually large eyes) compared to Western participants. Though Seyama and Nagayama hypothesize that cultural background moderates the Uncanny Valley effect, they do not include Western participants in their study to test this assumption. I know of no research which investigates this hypothesis.

While researchers commonly cite cultural background in their theoretical papers of presence, there remains little available empirical evidence one way or another.

Appendix I: Post Immersion Questionnaire (Full Items)

1) Please answer the following three questions about the task you just completed.

T.1 How many gift boxes do you remember finding in the task you just completed?

____

T.2 How many gift boxes do you think the *average participant* would find in the task you just completed?

____

T.3 If you were to do this same task again, one month from today, how many gift boxes do you think you would find?

____

2) Please rate the following statements about your virtual environment experience on a scale from 1 to 7, where 1 represents *strongly disagree* and 7 represents *strongly agree*.

P.1 I was able to control events.

1	2	3	4	5	6	7

P.2 The environment was responsive to actions that I initiated (or performed).

1	2	3	4	5	6	7

P.3 My interactions in the environment seemed natural.

1	2	3	4	5	6	7

P.4 The visual aspects of the environment involved me.

1	2	3	4	5	6	7

P.5 The auditory aspects of the environment involved me.

1	2	3	4	5	6	7

P.6 The mechanism which controlled movement through the environment was natural.

1	2	3	4	5	6	7

P.7 My sense of objects moving through space was compelling.

1	2	3	4	5	6	7

P.8 My experiences in the virtual environment seemed consistent with my real-world experiences.

1	2	3	4	5	6	7

P.9 I was able to anticipate what would happen next in response to the actions that I performed.

1	2	3	4	5	6	7

P.10 I was completely able to actively survey or search the environment using vision.

1	2	3	4	5	6	7

P.11 I could identify sounds.

1	2	3	4	5	6	7

P.12 I could localize sounds.

1	2	3	4	5	6	7

P.13 I could actively survey or search the virtual environment using touch.

1	2	3	4	5	6	7

P.14 My sense of moving around inside the virtual environment was compelling.

1	2	3	4	5	6	7

P.15 I was able to examine objects closely.

1	2	3	4	5	6	7

P.16 I could examine objects from multiple viewpoints.

1	2	3	4	5	6	7

P.17 I could move or manipulate objects in the virtual environment.

1	2	3	4	5	6	7

P.18 I was involved in the virtual environment experience.

1	2	3	4	5	6	7

P.19 I experienced delay between my actions and expected outcomes.

1	2	3	4	5	6	7

P.20 I adjusted quickly to the virtual environment experience.

1	2	3	4	5	6	7

P.21 At the end of the experience, I felt proficient in moving and interacting with the virtual environment.

1	2	3	4	5	6	7

P.22 The visual display quality interfered or distracted me from performing assigned tasks or required activities.

1	2	3	4	5	6	7

P.23 The control devices interfered with my performance of assigned tasks or with other activities.

1	2	3	4	5	6	7

P.24 I could concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities.

1	2	3	4	5	6	7

P.25 My senses were completely engaged in this experience.

1	2	3	4	5	6	7

P.26 It was easy to identify objects through physical interaction, like touching an object, walking over a surface, or bumping into a wall or object.

1	2	3	4	5	6	7

P.27 There were moments during the virtual environment experience when I felt completely focused on the task or environment.

1	2	3	4	5	6	7

P.28 I easily adjusted to the control devices used to interact with the virtual environment.

1	2	3	4	5	6	7

P.29 The information provided through different senses in the virtual environment (e.g., vision, hearing, touch) was consistent.

1	2	3	4	5	6	7

3) Please answer the following questions.

S.1 Please rate your *sense of being in the* virtual environment, on the following scale from 1 to 7, where 7 represents your *normal experience of being in a place.*

I had a sense of "being there" the virtual environment:						
1 Not at all	2	3	4	5	6	7 Very much

S.2 To what extent were there times during the experience when the virtual environment was the reality for you?

There were times during the experience when the virtual environment was the reality for me...						
1 At no time	2	3	4	5	6	7 Almost all the time

S.3 When you think back about your experience, do you think of the virtual environment more as *images that you saw* or more as *somewhere that you visited*?

The virtual environment seems to me to be more like...						
1 Images that I saw	2	3	4	5	6	7 Somewhere that I visited

S.4 During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment, or of being elsewhere?

I had a stronger sense of...						
1 Being else-where	2	3	4	5	6	7 Being in the virtual enviro-nment

S.5 Consider your memory of being in the virtual environment. How similar in terms of the *structure of the memory* is this to the structure of the memory of other *places* you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the virtual environment, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such *structural* elements.

I think of the virtual environment as a place in a way similar to other places that I've been today...						
1 Not at all	2	3	4	5	6	7 Very much so

S.6 During the time of the experience, did you often think to yourself that you were actually in the virtual environment?

During the experience I often thought that I was really standing in the virtual environment...						
1 Not very often	2	3	4	5	6	7 Very much so

4) Please rate the following statements about your virtual environment experience on a scale from 1 to 7, where 1 represents *strongly disagree* and 7 represents *strongly agree*.

F.1 The virtual environment felt real to me.

1	2	3	4	5	6	7

F.2 The objects in the virtual environment felt real to me.

1	2	3	4	5	6	7

F.3 While experiencing the virtual environment, I forgot that I was in the physical world.

1	2	3	4	5	6	7

F.4 While experiencing the virtual environment, my experience of the physical world was "dulled-down".

1	2	3	4	5	6	7

F.5 While experiencing the virtual environment, I found myself in the present moment, not thinking about past or future events.

1	2	3	4	5	6	7

Appendix J: Demographics Questionnaire (Full Items)

1) What is your date of birth?

_____Month _____Year

2) What is your biological sex?

Female Male

3) Without corrective lenses, do you have normal (20:20) vision or better?

Yes (If 'yes', then skip to #5)

No

4) If you don't have normal or better vision, did you wear eyeglasses or contacts that corrected your vision to normal during the experiment?

Yes

No (please enter acuity if known ________/________)

5) To your knowledge, are you color-blind?

Yes (please specify color-deficiency if known _________________________)

No

6) If you ever play video games, what kinds of games do you play?

____

____

____

7) In the last week how much time have you spent playing videogames?

________ hours ________minutes

8) In an average week, how much time do you spend playing videogames?

________ hours ________minutes

9) In the last week, outside of this study, how much time have you spent in a virtual reality headset?

________ hours ________minutes

10) In an average week, how much time do you spend in a virtual reality headset?

________ hours ________minutes

11) In your own words, what do you think was the purpose of the experiment?

____

____

____

____

____

____

____

____